EN671: Solar Energy Conversion Technology

Grid Connected PV System

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Design of a grid connected PV system

Preliminary study

- ❑ Study of the geographical setting of the location
- ❑ Analysis of climatic condition
- ❑ Selection of system
- ❑ Selection of PV technology (module)

Design of the system

- ❑ Selection of components (modules, inverter, cables combiner box etc.)
- ❑ PV array-inverter matching
  - ✓ No. of modules
  - ✓ No. on inverters
- ❑ Cable loss calculation
- ❑ Shading analysis

Performance analysis

- ❑ System energy production
- ❑ Performance ratio
- ❑ System losses

Preliminary study

Prior to designing any Grid Connected PV system a designer must know the **geographical setting of the location and must** visit the site :

- Determine the solar access for the site.
- Determine whether any shading will occur and estimate its effect on the system.
- Determine the orientation and tilt angle of the roof/site.
- Determine the available area for the solar array.
- Determine whether the roof is suitable for mounting the array in case of roof mounted system.
- Determine how the modules will be mounted on the roof/site.
- Determine where the inverter will be located.
- Determine the cabling route and therefore estimate the lengths of the cable runs.

Following the site visit the designer shall estimate the **available solar irradiation for the array** based on the available solar irradiation for the site, tilt, orientation and effect of any shadows.

Preliminary study

Analysis of Climatic condition of the location

Various parameter defining the climatic condition of a particular location can be obtained from respective meteorological department. Furthermore, location wise climatic data can also be collected from NASA meteorological department available online at *http:/eosweb.larc.nasa.gov/sse/*

Parameters considered for analyzing the climatic scenario of a particular location:

- ✓ Monthly average daily normal radiation (DNI)
- ✓ Monthly average insolation incident on a horizontal surface
- ✓ Monthly average clear sky insolation, clearness index
- ✓ Monthly average daylight hours
- ✓ Daily sunshine hours
- ✓ Monthly average wind speed
- ✓ Monthly average relative humidity
- ✓ Monthly average air temperature
- ✓ Monthly average rainfall

Design of the system

Selection of the components

BIS: Bureau of Indian Standards
IEC: International Electrotechnical Commission
IP: Ingress Protection Code
IS: Indian Standard
EN: European Standards
BS: British Standards

- System design should follow appropriate standard.
- Country wise these standards may vary.
- Components with applicable BIS /Equivalent IEC Standard or MNRE Specifications :

→ **Solar PV module: IEC 61215/ IS 14286:** Design qualification and type of approval for crystalline silicon terrestrial PV modules.

→ **Inverter: IEC 62109-1, IEC 62109-2:** Safety of power converters for use in photovoltaic power systems –

- → Part 1: General requirements, and Safety of power converters for use in photovoltaic power systems.
- → Part 2: Particular requirements for inverters. Safety compliance (Protection degree **IP 65** for outdoor mounting, IP 54 for indoor mounting).

→ **Cables: BS EN 50618:** Electric cables for photovoltaic systems (BT(DE/NOT)258), mainly for DC cables.

Design of the system

Selection of the components

→ **Connectors:** Certified for applications with modules according to **IEC 61730**

→ **Array box Protection: IP 65:** enclosures with transparent covers with Surge Protection Device (SPD) class-I/II, DC Fuse with holder and string disconnector.

→ **Module mounting structure: IS 2062 / IS 4759:** Material for the structure mounting

→ **Lightning Arrestor: IEC 62561 Series**

→ **Weather monitoring system: IS/IEC 61724 (1998):** Photovoltaic System Performance Monitoring - Guidelines for Measurement, Data exchange and Analysis

→ **Supervisory control and data acquisition (SCADA): IEC 61850:** Protocol defined for substation automation

→ **Fuses: IS/ IEC 60947 (Part 1, 2 & 3), EN 50521**: General safety requirements for connectors, switches, circuit breakers (AC/ DC); **IEC 60269-6**: Low-voltage fuses

Designing grid-connected PV system

Designing a PV system based on the energy balance paradigm.

(The generated energy = the consumed energy during one year).

The energy yield at the DC side is given by:

$$E_{DC}^{y} = A_{tot} \int G_M(t)\eta(t)\, dt \text{..........(1)}$$

A_{tot} is the total module area.

It is related to the area of one module A_M as:

$$A_{tot} = N_T \cdot A_M \text{.................................(2)}$$

where N_T is the number of modules.

The required energy balance:

$$E_{DC}^{y} = E_L^{y} \cdot \mathrm{SF} \text{ ....(3)}$$

SF is a sizing factor that usually is assumed to be 1.1.

Designing grid-connected PV system

- The required number of modules is given by:

$$N_T = \left\lceil \frac{E_L^y \cdot \mathrm{SF}}{A_{tot} \int G_M(t)\eta(t)\, dt} \right\rceil \text{.........(4)}$$

where $\lceil x \rceil$ denotes the ceiling function, i.e. the lowest integer that is greater or equal than x.

- The number of modules in connected in series N_S and in parallel N_P are denoted by:

$$N_T = N_S . N_S \text{ ....(5)}$$

Example-
If N_T = 11 panels, it can be taken as N_T = 12 because they can be installed as S×P= 12 × 1, 6 × 2, 4 × 3, 3 × 4, 2 × 6 or 1 × 12 strings.

Designing grid-connected PV system

- The power on the DC side at STC now is given as:

$$p_{DC}^{STC} = \mathrm{N_T} \, . \, p_{MPP}^{STC} \; ....(6)$$

$$p_{DC,max}^{inv} > p_{DC}^{STC} \; ....(7)$$

- Further, the nominal DC power of the inverter should be approximately equal to the PV power at STC

$$\mathrm{P_{DC0}} \approx p_{DC}^{STC} \; ....(8)$$

In practice, the nominal DC power of the inverter is selected slightly below the PV power at STC, (up to 10%), depending on the climate zone, because of the different irradiance distributions. Also, for P_{DC0} < 5 kWp, single-phase inverters are used while for P_{DC0}> 5 three-phase inverters are advised.

Design of the system

Specification of a 300 Wp solar module (manufacture *TATA power solar)*

Electrical parameters at standard test conditions (STC)						
Power output (W)	Module efficiency (η %)	Voltage at P_{MAX} V_{MPP} (V)	Current at P_{MAX} I_{MPP} (A)	Open-circuit voltage V_{OC} (V)	Short-circuit current I_{SC} (A)	Power tolerance (W)
300	15.10	36.6	8.20	44.8	8.71	0 ~ +5
Temperature coefficient characteristics						
NOCT (°C)	Module efficiency (%/°C)	Temperature coefficient of P_{MAX} (%/°C)	Temperature coefficient of V_{OC} (%/°C)	Temperature coefficient of I_{SC} (%/°C)	---	---
47 ± 2	0.06 ± 0.01	0.4048	0.2931	0.0442	---	---

Specification of an inverter manufactured by *Bonfiglioli*

Input Data (DC)			
Max. DC Power	Max. DC Voltage	Max. DC Current	MPP(T)Voltage Range
280 kW	900 V	600 A	425-975 V
Output Data (AC)			
Max. AC Power	Output AC Voltage Range	Max. AC Current	Max. Efficiency
250 kW	270-330 V	540 A	98.3%

Design of the system

Matching inverter and array

- **It is important to find out the most appropriate combination of module and inverters by considering the local operating conditions.**
- **The voltage, current and power rating, of module and inverter are the three criteria which ensure the proper matching of the system in terms of performance and safety.**
- The important steps related to matching of inverter and PV modules are
    - *Number of modules in a string*
    - *Maximum number of strings (to match with inverter input)*
    - *Matching the power rating*

Design of the system

Matching inverter and array

Number of modules in a string

→ The first is to determine the lower and upper limit of a string, i.e. minimum and maximum numbers of modules that can be connected in series.

→ **maximum and minimum operating temperature**

→ **maximum and minimum effective voltage of the module**

→ Maximum and minimum operating temperature

By knowing the ambient temperature of a particular location, NOCT (Nominal Operating Cell Temperature) of the PV module and the incident solar radiation at that location the module operating temperature can be calculated as

$$T_{op} = T_{amb} + \frac{(NOCT - 20)}{800} \times G$$

where, G is Solar intensity

The maximum operating temperature and minimum operating temperature can be calculated using this **equation** by considering recorded highest and lowest ambient temperature of a particular location.

Design of the system

Matching inverter and array

Number of modules in a string

→ *Minimum and maximum effective voltage of the module*

The minimum and maximum effective voltage of PV array can be calculated using following **equations:**

$$V_{Min-Eff} = V_{MP-STC} - \left[\gamma_p \times \left\{ \left(T_{op} \right)_{\max} - T_{STC} \right\} \right]$$

$$V_{\mathrm{Max}-Eff} = V_{OC-STC} - \left[\gamma_{V_{oc}} \times \left\{ \left(T_{op} \right)_{\min} - T_{STC} \right\} \right]$$

Note: It is very important to keep in mind that the output voltage of the array should not fall outside the inverter's MPPT voltage range

Design of the system

Matching inverter and array

Number of modules in a string

- *Minimum number of modules in a string can be calculated using the equation*

$$\left(M_{String}\right)_{\min} = \frac{\left(V_{Inv-DC}\right)_{\min}}{V_{Min-Eff}}$$

Note: There is a voltage drop which occurs when the generated electricity flows from array to inverter. Therefore, during the calculation of lower limit, a 2% voltage drop needs to be considered for $V_{min\text{-}eff}$ and a safety margin of 10% should be considered for $(V_{inv\text{-}DC})_{min}$

- *Maximum number of modules in a string can be calculated using the equation*

$$\left(M_{String}\right)_{\max} = \frac{\left(V_{Inv-DC}\right)_{\max}}{V_{Max-Eff}}$$

Note: For calculation of $V_{max\text{-}eff}$, open-circuit voltage is considered since there is no voltage drop. But for calculation of $(V_{inv\text{-}DC})_{max}$ 5% safety margin is applied

Design of the system

Matching inverter and array

Maximum number of strings (to match with inverter input)

- Current rating of the module has to be matched with the inverter's input current rating in order to determine the maximum possible strings to be connected in parallel with the inverter.
- Due to the variation in operating temperature, the value of short-circuit current of the module also differs from its STC value, which can be determined as;

$$I_{SC-Eff} = I_{SC-STC} - \left[\gamma_{I_{sc}} \times \left\{ \left(T_{op} \right)_{\max} - T_{STC} \right\} \right]$$

- Maximum number of strings to be connected in parallel with the inverter can be determined using the following equation

$$\left(S \right)_{\max} = \frac{I_{Inv-DC}}{I_{SC-Eff}}$$

$\gamma_{I_{sc}}$ = Short-circuit temeprature coefficient (%/^{o}C)

γ_{P} = Maximum power temperature (%/^{o}C)

γ_{Voc}= Open circuit voltage temeprature coefficient (%/^{o}C)

Design of the system

Matching inverter and array

Matching the power rating

- ✓ Match the best combination of strings and arrays to get the maximum DC power output.
- ✓ The maximum DC power output of the PV array should always $\leq$ to the input DC power of the inverter.

For Example

No. of modules per string	No. of strings per array	Total power output (kW)
$(M_{string})_{min}$ =16	59	283.20
	58	**278.40**
	57	273.60
$(M_{string})_{max}$ = 17	55	280.50
	54	275.40
	53	270.30

Closest no. max. input DC power of the Inverter

Design of the system

Selection of cable

The following formulas can be used to determine the cross sectional area of the cables

For DC cable

$$A_{DCcable} = \frac{2 \times L_{DCcable} \times I_{DC} \times \rho}{Loss \times V_{MP\,string}}$$

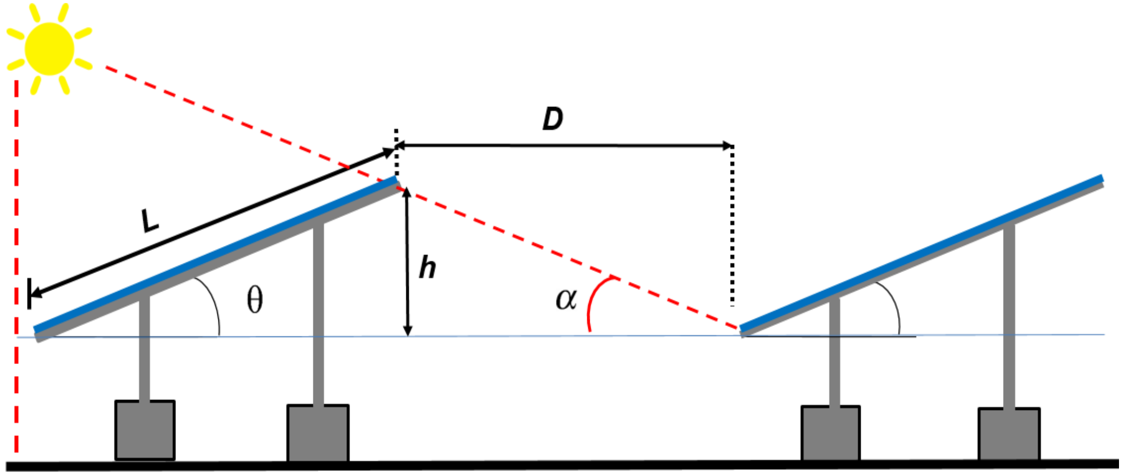
For AC cable

$$A_{ACcable} = \frac{2 \times L_{ACcable} \times I_{AC} \times \rho \times \cos\phi}{Loss \times V_{AC}}$$

Design of the system

Shading analysis

- The minimum distance between two solar modules (inter-row distance), which is to be maintained in order to prevent mutual shading.



D = 3 x h

$$\sin\alpha = \sin\phi \times \sin\delta + \cos\phi \times \cos\delta \times \cos\omega$$

$$\cos\psi = \frac{\cos\delta \times \sin\omega}{\cos\alpha}$$

$$L_{SH} = \frac{h \times \cos\psi}{\tan[\sin^{-1}(0.648\cos\phi - 0.399\sin\phi)]}$$

$$D = L_{SH} \times \cos\alpha$$

$$h = L \times \sin\theta$$

L_{SH} = Shadow length, m

α = Sun elevation angle

ϕ = Latitude

δ = Declination

ψ = Sun azimuth angle

ω = Hour angle

θ = solar module tilt angle

Ex.1 A solar power plant is to be installed at IIT Guwahati campus to meet the electricity demand of 2 MW at a solar insolation of 800 W/m^2. Manufacturers output tolerance, derating due to dirt and derating due to temperature of a PV module are 5%, 5% and 0.5%/°C respectively. DC cable loss, inverter efficiency and AC cable loss are 3%, 98.3% and 1% respectively. The inverter has a maximum voltage input of 900 V and maximum DC current input of 600 A. The detailed specification of the module and inverter are given in the tables-1 and 2 respectively. The minimum temperature, maximum temperature and solar peak hour of the site are reported to be 5 ^{0}C, 38^{0}C and 5 hrs. respectively. Find out the total number of modules required for the plant. Also estimate the DC output from the array.

Table 1 Specifications of module

Electrical parameters at standard test conditions (STC)						
Power output (W)	Module efficiency (η %)	Voltage at P_{MAX} , V_{MPP} (V)	Current at P_{MAX} I_{MPP} (A)	Open-circuit voltage V_{OC} (V)	Short-circuit current I_{SC} (A)	Power tolerance (W)
300	15.10	36.6	8.20	44.8	8.71	0 ~ +5
Temperature coefficient characteristics						
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47 ± 2	-0.06 ± 0.01	0.4048	0.2931	0.0442	---	---

Table 2 Technical specifications of inverter

Input Data (DC)			
Max. DC Power	Max. DC Voltage	Max. DC Current	MPP(T)Voltage Range
280 kW	900 V	600 A	425-975 V
Output Data (AC)			
Max. AC Power	Output AC Voltage Range	Max. AC Current	Max. Efficiency
250 kW	270-330 V	540 A	98.3%

Different possible arrangement of module array

	No. of modules per string	No. of string per array	Power output , STC (kW)	De-rated Power Output (kW)
Minimum String	12	69	248.4	190.553436
	12	72	259.2	198.838368
	12	74	266.4	204.361656
	12	76	273.6	209.884944
	12	77	277.2	212.646588
	12	78	280.8	215.408232
	12	80	288	220.93152
	12	90	324	248.54796
	12	100	360	276.1644
	12	**101**	363.6	278.926044
	12	102	367.2	281.687688
Maximum String	22	69	455.4	349.347966
	22	65	429	329.09591
	22	60	396	303.78084
	22	55	363	278.46577
	22	50	330	253.1507
	22	45	297	227.83563
	22	43	283.8	217.709602
	22	42	277.2	212.646588
	16	58	278.4	
	16	76		279.68

For 2 MW power plant, the number of modules required will be: 7392/9698 nos.

Summary

- Design of a grid connected PV system.
- Operating temperature of the module plays an important role in matching of PV array with the inverter.
- The voltage, current and power ratings, of module and inverter are the three criteria which ensures a proper matching of the system in terms of performance and safety.
- Design steps:
  - Derating of module
  - min and max operating temperature of the module
  - min and max effective voltage of module
  - lower and upper limit of string (min and max no of module to be connected in series)
  - matching of current rating of the module with the inverter input current rating to determine possible string to be connected in parallel.
  - Possible arrangement of module array.
- Sizing of inverter based on the size of the array.
- Demonstrated how to design a grid connected PV system

Thank you