EN671: Solar Energy Conversion Technology

Standalone Photovoltaic System

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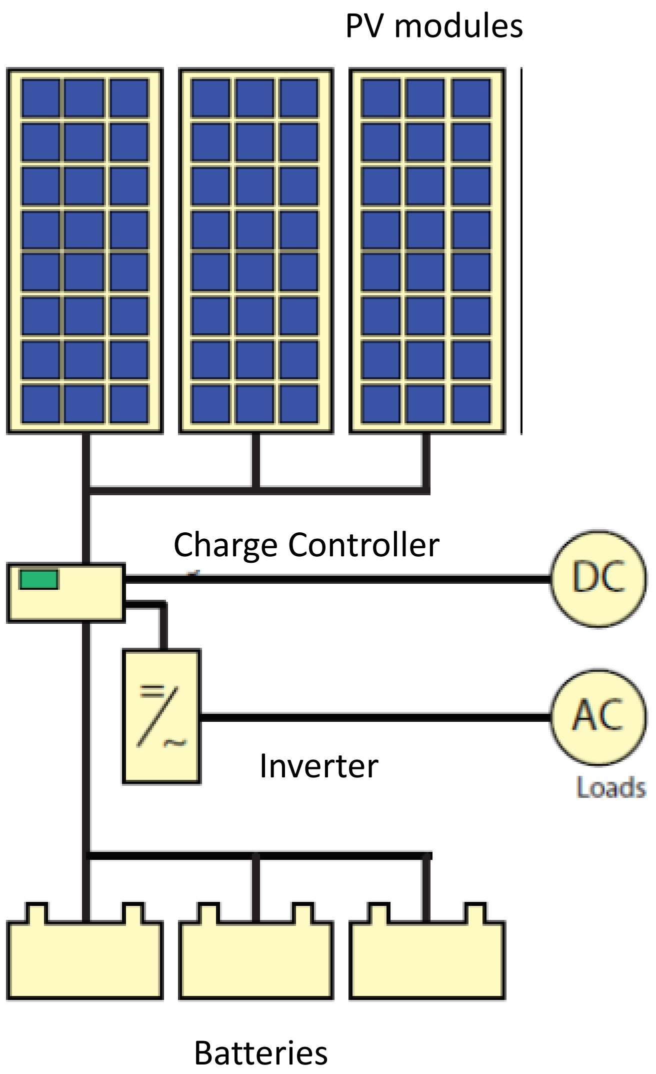
Design principle of a standalone(off grid) PV system



Design principles and steps

A major component of off-grid systems is the storage component, which can store energy in times when the PV system generate more electricity than required and it can deliver energy when the electricity generated by the PV modules in not sufficient.

Required number of autonomy, i.e. the number of days a fully charged storage must be able to deliver energy to the system until discharged.

The sizing of both the PV array and the storage component (battery bank) are interconnected. Here, two situations arises.

1. E_{fail}, which is the energy required by the electric load that cannot be delivered by the PV system (if the batteries are emptied after several cloudy days).

2. E_{dump}, which is the energy produced by the PV array that neither is used for driving a load nor is stored in the battery (if the batteries are already full after a number of sunny days).

Sizing based on the reliability of supply

- ✓ The reliability of electricity supply is an important factor in PV system design.
- ✓ One way to quantify the reliability of supply is by a parameter known as the **loss-of load probability (LLP)**, [ratio between the estimated energy deficit and the energy demand over the total operation time of the installation].

Application	Recommended LLP
Domestic illumination	0.1
Appliances	1
Telecommunications	0.001

$$\mathrm{LLP} = \frac{E_{fail}}{\int_{year} P_L(t)\,dt}$$

Load profile is varying

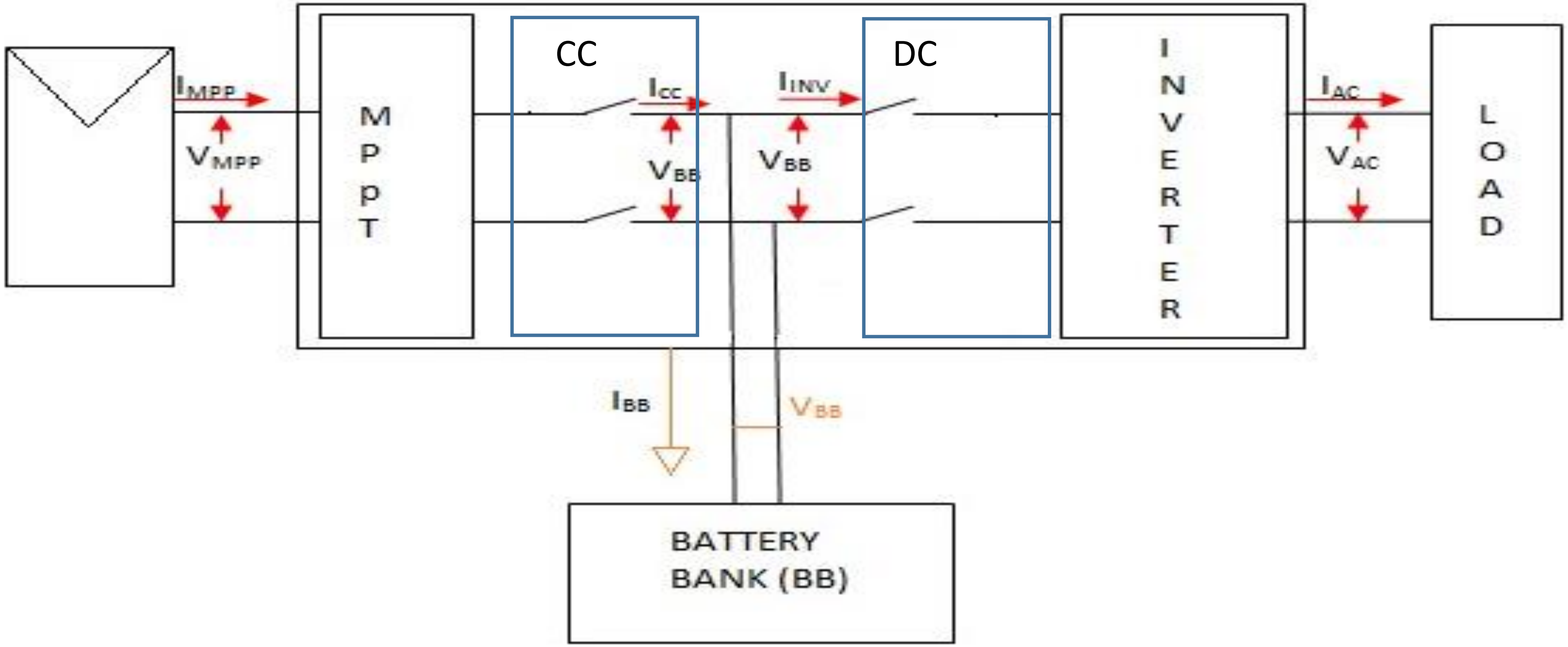
Total Energy consumed in a year: $E_L = \int_{year} P_L(t)\,dt$

kWh/Year

Lower the LLP, more stable and reliable the PV system would be .

Prevents the BB from being overcharged by the PV system.

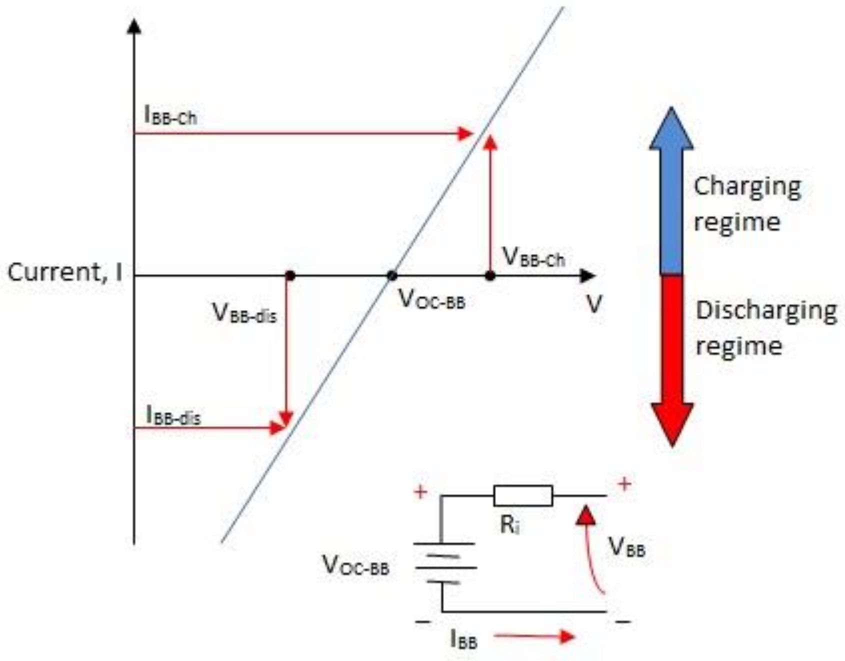
Prevents the battery to be discharged below the minimal allowed SoC.



Schematic of an off-grid system

The battery bank

- Battery bank is the workhorse of any off-grid system, because it is stable power source.
- It is thus very important to understand how the battery bank will act in the PV system.



I-V curve of an idealised battery bank

To know how a battery works the net effect of all the forces that try to charge or discharge the battery need to be understood.

V_{OC-BB} will not be constant, but a function of the state of charge, the ambient temperature, and others.

$V_{OC\text{-}BB}$ assumed to be constant. Because of R_i, the voltage V_{BB} will differ from $V_{OC\text{-}BB}$ and also is dependent on the current I_{BB} flowing through the battery,

I_{BB} is positive when the battery is charged and negative when it is discharged.

$$I_{\mathrm{BB}} = \frac{1}{R_i}\left(V_{\mathrm{BB}} - V_{\mathrm{OC\text{-}BB}}\right)$$

Now derive an expression for the voltage of the battery bank (V_{BB}) as a function of the other PV system parameters.

The power on the left and right-hand sides of the MPPT,

$$\eta_{\mathrm{MPP}} I_{\mathrm{MPP}} V_{\mathrm{MPP}} = I_{\mathrm{CC}} V_{\mathrm{BB}} =: \beta \quad \Rightarrow \quad I_{\mathrm{CC}} = \frac{\eta_{\mathrm{MPP}} I_{\mathrm{MPP}} V_{\mathrm{MPP}}}{V_{\mathrm{BB}}} = \frac{\beta}{V_{\mathrm{BB}}}$$

Consequently, *β= 0 means that the PV system is not active*, for example during night. In a similar manner.

The power on the left and right hand side of the inverter:

$$P_L = I_{AC}V_{AC} = \eta_{inv} I_{inv} V_{BB} =: \eta_{Inv}\alpha,$$

$$I_{inv} = \frac{P_L}{\eta_{inv} V_{BB}} = \frac{\alpha}{V_{BB}}$$

$$I_{CC} = \frac{\eta_{MPP} I_{MPP} V_{MPP}}{V_{BB}} = \frac{\beta}{V_{BB}} \qquad I_{inv} = \frac{P_L}{\eta_{inv} V_{BB}} = \frac{\alpha}{V_{BB}}$$

$$I_{BB} = I_{CC} - I_{inv} = \frac{\beta - \alpha}{V_{BB}}.$$

Clearly, *a = 0 indicates that no load is present.*

$$I_{\mathrm{BB}} = \frac{1}{R_i}\left(V_{\mathrm{BB}} - V_{\mathrm{OC\text{-}BB}}\right) \qquad I_{\mathrm{BB}} = I_{\mathrm{CC}} - I_{\mathrm{inv}} = \frac{\beta - \alpha}{V_{\mathrm{BB}}}.$$

Combining above equations and multiplying with $\boldsymbol{R_i V_{BB}}$ and rearranging leads to a quadratic equation,

Quadratic equation:

$$V_{\mathrm{BB}}^2 - V_{\mathrm{OC\text{-}BB}} V_{\mathrm{BB}} - R_i(\beta - \alpha) = 0.$$

Solutions:

$$V_{\mathrm{BB}}^{\pm} = \frac{V_{\mathrm{OC\text{-}BB}}}{2} \pm \sqrt{\left(\frac{V_{\mathrm{OC\text{-}BB}}}{2}\right)^2 + R_i(\beta - \alpha)}.$$

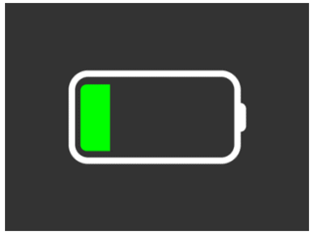
The correct solution is the "+" solution

$$V_{\mathrm{BB}}^{+}(\beta - \alpha = 0) = V_{\mathrm{OC\text{-}BB}}$$

Hence, the final solution is

$$V_{\mathrm{BB}} = \frac{V_{\mathrm{OC\text{-}BB}}}{2} + \sqrt{\left(\frac{V_{\mathrm{OC\text{-}BB}}}{2}\right)^2 + R_i(\beta - \alpha)}.$$

Charging



- If the battery is charged, I_{CC} is higher than I_{inv} and hence **(β-a)** *and* I_{BB} *are positive.*

- V_{BB} is higher than $V_{OC\text{-}BB}$.

Discharging

- If the battery is discharged, I_{CC} is lower than I_{inv} and hence **(β-a)** *and* I_{BB} *are negative.*
- V_{BB} will be lower than $V_{OC\text{-}BB}$.

The net current $I_{BB} = I_{CC}$ flows in or out of the battery. Therefore, only this current determines the power loss in the battery,

$$P_{BB}(\text{loss}) = I_{BB}^2 R_i$$

This power always is lost, irrespective of the sign of I_{BB}.

Recommended number of autonomous days at several latitudes

Latitude (°)	Recommended d_A
0-30	5-6
20-50	10-12
50-60	15

Designing a system with energy balance

The analysis for the load side and the PV side is performed separately.

Let us begin with the the load side.

Determine the annual load,

$$E_L^Y = \int_{\text{year}} P_L(t)\,\mathrm{d}t$$

Determine the average daily load

$$E_L^D = \frac{1}{365} E_L^Y$$

Calculation of the required energy of the battery bank,

$$E_{\text{BB}} = d_A \frac{E_L^D \cdot \text{SF}_{\text{bat}}}{\text{DoD}_{\text{max}}}$$

✓SF_{bat} is the sizing factor of the battery.

✓DoD_{max} is the maximally allowed depth of discharge of the batteries.

An adequate **number of days of autonomy (d_A)** need to be selected depending the location and a basic understanding of weather pattern.

Calculation of the required number of batteries,

$$N_{\text{bat}} = \left\lceil \frac{E_{\text{BB}}}{E_{\text{bat}}} \right\rceil$$

The rated energy of the chosen batteries is

$$E_{\text{bat}} = V_{\text{OC-bat}} C_{\text{bat}}$$

where C_{bat} is the battery capacity (unit Ampere-hours).

Inverter selection

- Consider the maximal load power.
- It may be more beneficial to choose a system design, such that not all appliances can be used at the same time.

Requirements:

1 The maximally allowed power output must exceed the maximal power required by the appliances,

$$P^{\mathrm{inv}}_{\mathrm{DC,\,max}} > P^{\mathrm{max}}_{L}.$$

2 The nominal power of the inverter should be approximately equal to the maximal load power,

$$P_{\mathrm{DC},0} \approx P^{\mathrm{max}}_{L}$$

3 The nominal inverter input voltage should be approximately equal to the nominal voltage of the battery back,

$$V_{\mathrm{DC,\,inv}} \approx V_{\mathrm{OC\text{-}BB}}$$

Adjustment of the batteries

Typical voltages for the battery bank are 12 V, 24 V, 48 V or 96 V.

It can be adjusted by the number of batteries that are connected in series,

$$\boxed{N_{\text{bat}}^{S} = \frac{V_{\text{OC-BB}}}{V_{\text{OC-bat}}}}$$

The number of batteries that must be connected in parallel,

$$\boxed{N_{\text{bat}}^{P} = \left\lceil \frac{N_{\text{bat}}}{N_{\text{bat}}^{S}} \right\rceil}$$

PV side of the system

The energy balance can be written down as

$$\boxed{E_{\mathrm{DC}}^{Y} = E_{L}^{Y} \cdot \mathrm{SF}}$$

Sizing factor (SF) is usually assumed to be 1.1

The required number of modules

$$\boxed{N_T = \left\lceil \frac{E_L^Y \cdot \mathrm{SF}}{A_M \cdot \int_{\mathrm{year}} G_M(t)\eta(t)\,\mathrm{d}t} \right\rceil}$$

For minimising losses, the MPP voltage of the PV array and the nominal voltages of the inverter and the battery pack should be approximately equal.

The number of PV modules that are connected in series in the PV array

$$\boxed{N_S = \left\lfloor \frac{V_{\text{OC-BB}}}{\overline{\overline{V}}_{\text{mod-MPP}}} \right\rfloor}$$

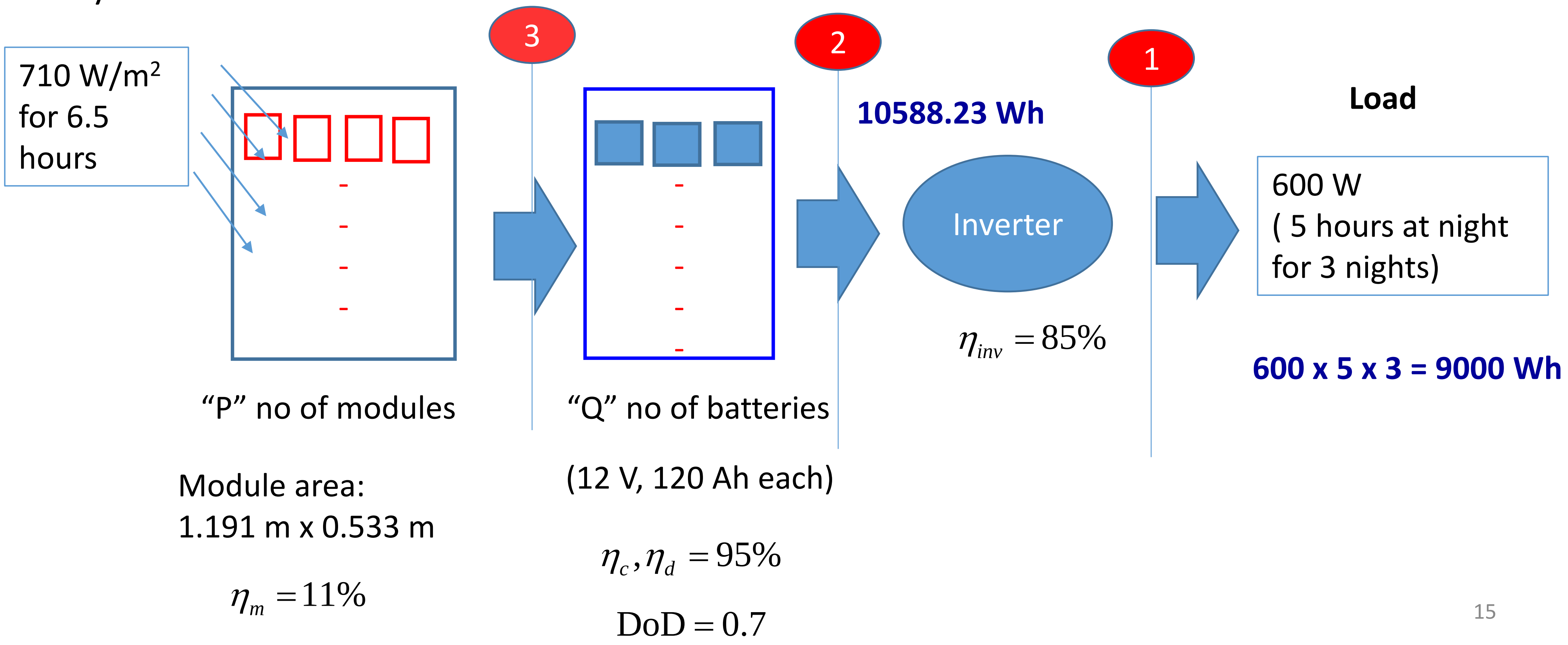
$V_{\text{MPP-mod}}$ denotes the annual average of the MPP voltage of the PV modules. Of course, the maximally allowed input voltage of the MPPT-CC unit must not be exceeded by the PV array,

$$\boxed{V_{\mathrm{MPP}} \geq N_S \cdot V_{\text{mod-MPP}}^{\max}}$$

The number of required parallel PV strings

$$\boxed{N_P = \left\lceil \frac{N_T}{N_S} \right\rceil}$$

Q1: A residential house has a power requirement of 600 W for 5 hours every night. It is proposed to meet the requirement by using a PV array, a battery storage system and an inverter. The whole system is over designed so that it can meet two extra night's requirement even if there has been no sunshine during those days. Calculate the number of PV modules and batteries required. Given that (i) the solar radiation is available for an average of six and half hours daily and the average hourly global radiation flux incident on the array is 710 W/m^2; (ii) Battery rating = 12 V; 120 Ah, depth of discharge = 0.8, charging efficiency = 0.95, and discharging efficiency = 0.95; (iii) Inverter efficiency at full load = 0.85, (iv) efficiency of the module = 11%.



Let P and Q are the number of modules and batteries required

The daily energy output from PV array (at 3):

$$E_{PV-output} = I_g \times SPH \times A_m \times P \times \eta_m$$
$$E_{PV-output} = 710 \times 6.5 \times (1.191 \times 0.533) \times P \times 0.11 = 322.25 \times P \text{ Wh}$$

Total load, at 1,

$$\mathrm{E}_L = 600 \times 5 (\text{daily 5 hours operation}) \times 3 (\text{for 3 days}) \text{ Wh}$$
$$\mathrm{E}_L = 9000 \text{ Wh}$$

The power available at the load

$$E_L = E_{PV-output} \times \eta_c \times \eta_d \times \eta_{inv}$$
$$= 322.25 \times P \times 0.95 \times 0.95 \times 0.85$$
$$= 247.20 \times P \text{ Wh}$$

Total load and power available at the load is equal, hence,

$$E_L = 247.20 \times P \text{ Wh} = 9000 \text{ Wh}$$
$$\Rightarrow P = 36.4 \cong 37$$

Energy Supplied by one battery to the load,

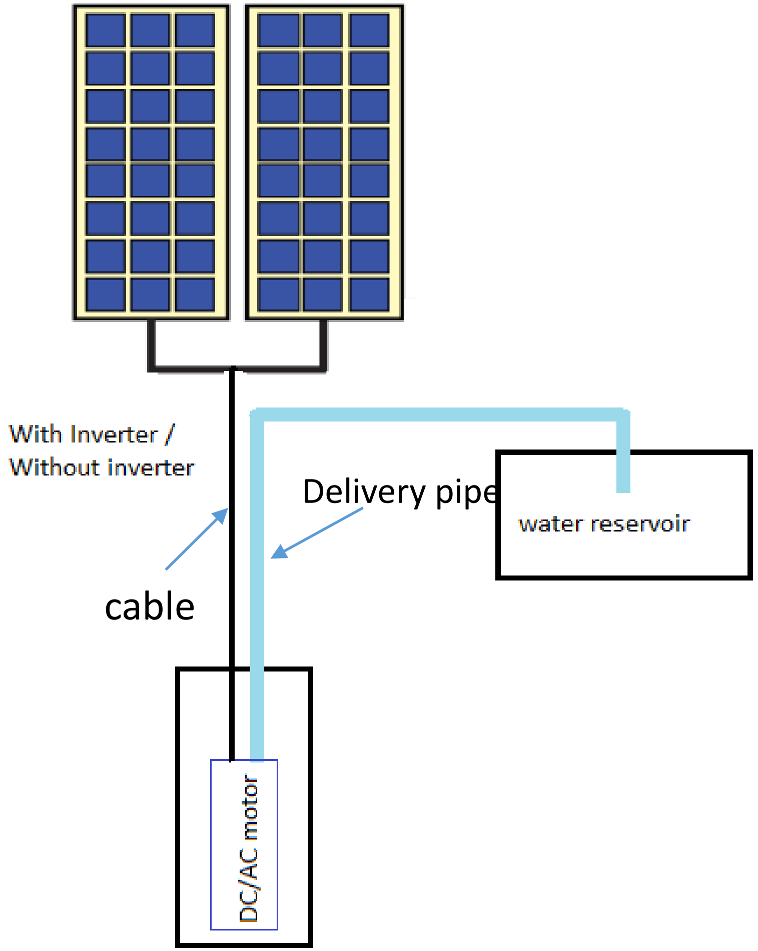
$$E_B = V \times Ah \times \eta_d \times \eta_d \times \eta_{inv}$$
$$\Rightarrow E_B = 12 \times 120 \times 0.8 \times 0.95 \times 0.85 = 930.24 \text{ Wh}$$

Number of batteries required,

$$Q = \frac{E_L}{E_b} = \frac{9000}{930.24} = 9.67 \cong 10$$

Photovoltaic water pumping system

- System can pump water from depths of 20 – 100 meters
- Supply water from 5000 – 50000 litres/day
- PV system supplies power through a dc-ac inverter to an electric motor coupled to a submersible pump.

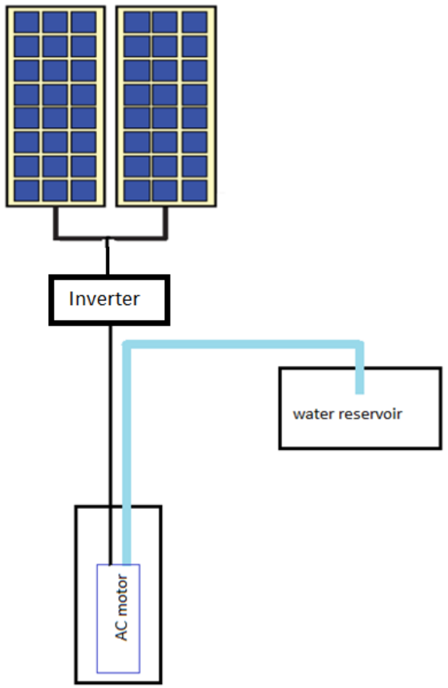


Q2: A photovoltaic system is installed for supplying water for minor irrigation purpose at a remote place in a developing country. The water is pumped through a bore well from a depth of 40 m. The PV array consists of 24 modules. Each module has 36 mutlicrystalline silicon solar cells arranged in 9 x 4 matrix. The cell size is 125 mm x 125 mm and the cell efficiency is 12%. Consider the efficiency of inverter and the combined motor and pump efficiency are 85% and 50 % respectively. Calculate the water discharge rate at noon when global radiation incident normally to the panel is 800 W/m^2. Assume the density of fresh water as 1000 kg/m^3.

$$\text{Conversion efficiency} = \frac{\text{Power output from array}}{\text{Incident solar flux} \times \text{cell area}}$$

$$\Rightarrow \eta_c = \frac{P_{PV-output}}{I_g \times A_c}$$

$$\Rightarrow 0.12 = \frac{P_{PV-output}}{800 \times 9 \times 4 \times (0.125 \times 0.125) \times 24} \Rightarrow P_{PV-output} = 1296 \text{ W}$$



Power available for lifting water $P = P_{PV-output} \times \eta_{inv} \times \eta_m = 1296 \times 0.85 \times 0.5 = 550.80 \text{ W}$

We have, $P = \rho \times g \times Q \times H$

Water discharge rate, $Q = \dfrac{P}{\rho \times g \times H} = \dfrac{550.80}{1000 \times 9.81 \times 40} = 1.40366 \times 10^{-3}\ \text{m}^3/\text{s} = 5053.21 \text{ litre/hr}$

Summary

- Design principle of standalone (off grid) PV system.
- Step by step procedure for design of PV system.
- Photovoltaic water pumping system
- Numerical exercise.

Thank you