Q.1 Explain how crystalline Silicon converts sunlight into electricity in PV cells.

crystalline silicon converts sunlight into electricity by utilizing the photovoltaic effect, where absorbed light energy generates charge carriers (electrons and holes), and the PN junction drives these carriers to create current and voltage across the external load.

Q.2 What is the theoretical maximum conversion efficiency of Silicon based solar PV cells? Explain the reason behind this.

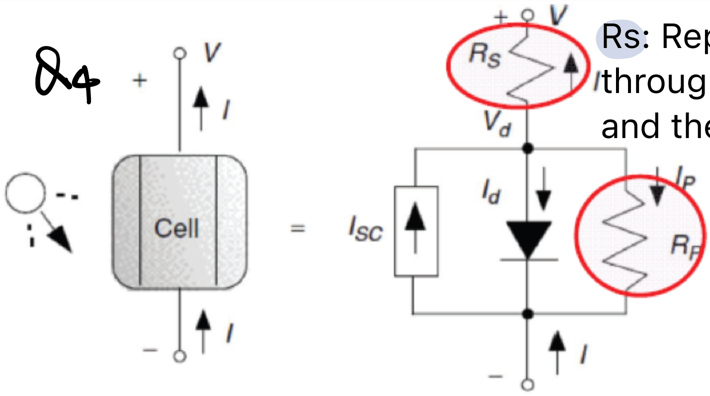
Q.3 What are the various losses in PV cells which reduce the conversion efficiency below the theoretical maximum efficiency?

Q.4 Draw the complete equivalent circuit of the solar PV cell. Explain the principle behind each component in the equivalent circuit.

Efficiency of PV Cell (光伏电池效率)

- Efficiency drops to 49.6% due to losses caused by photons with insufficient or too much energy. Q2
- Further drop in efficiency due to:
  1. Recombination of holes and electrons before they can contribute to current flow. Q3
  2. Only about half to two-thirds of the full band-gap voltage across the terminals of the solar cell.
  3. Photons that are not absorbed in the cell
  4. Internal resistance within the cell, which dissipates power

Q4



Rs: Represents the resistance due to the flow of current through the material of the solar cell, the metal contacts, and the interconnections.

Rp: Represents leakage paths for current within the solar cell, caused by defects or impurities.

Id: Models the current flowing through the diode (the p-n junction) in the forward direction.

- Denoted as I_{sc}, it is the current produced by the solar PV cell when its terminals are short-circuited (voltage $V = 0$).

Q.5 Find the open circuit voltage of solar PV cell with the following information given. Ambient temperature 40°C. Boltzmann constant k= 1.381 X 10^{-23}, charge of electron q=1.602X10^{-19} C. Short circuit current is 4A and the reverse saturation current is 10^{-10} A.

open circuit voltage of solar PV cell

$$V_{OC} = \frac{kT}{q} \ln\left(\frac{I_{SC}}{I_0} + 1\right)$$

$T = 40°C = 273 + 40 = 313K$ $\quad \frac{KT}{q} = \frac{1.381 \times 10^{-23} \times 313}{1.602 \times 10^{-19}} = 0.0269V$

$V_{oc} = \frac{0.0269}{1} \ln\left(\frac{4}{10^{-10}} + 1\right) \approx 0.65V$

I_0: reverse saturation current $\quad I_{sc}$: short circuit current

Q.6 A solar PV module with 32 cells in series supplies 2A to a 5Ω load. The ambient temperature is 25°C. The parallel and series resistors in the PV cell equivalent circuit are 10Ω and 0.1Ω respectively. The reverse saturation current of the junction is 10^{-10}A. Determine the short circuit current of the cell.

$n=32$ $I=2A$ $V=2A\times5\Omega=10V=n(V_d-IR_s)$

LOAD → 5Ω

$R_p=10\Omega$ $R_s=0.1\Omega$ $I_0=10^{-10}A$

$V_d=\frac{10}{32}+2\times0.1$
$=0.5125V$

求 Isc.

$$I_{sc}=I+I_0(e^{38.9V_d}-1)+\frac{V_d}{R_p}$$

$$=2+10^{-10}(\underbrace{e^{38.9\times0.5125}}_{19.93}-1)+\frac{0.5125}{10}=2.0965.$$

Q.7 The loss due to series and parallel resistors in the equivalent circuit of the PV cell are less that 1 percent. Determine the limits of their values if the $V_{OC}=0.6\ V$ and $I_{SC}=4\ A$.

$V_{oc}=0.6V$ $I_{sc}=4A$

$V_{ideal}=0.6\times4=2.4W$

① $I^2R_s<0.01\times2.4$

$16\times R_s<0.01\times2.4$

$R_s<0.0015\Omega$

② $\frac{V^2}{R_p}<0.024$

$\frac{(0.6)^2}{R_p}<0.024$

$R_p>15\Omega$

解题思路

光伏电池的输出功率会受到串联电阻 R_s 和并联电阻 R_p 的影响：

1. **串联电阻** R_s：会导致电压损失 $V_{\text{loss, series}}=I\cdot R_s$。
   串联电阻的功率损耗：
   $$P_{\text{loss, series}}=I^2\cdot R_s$$
2. **并联电阻** R_p：会导致泄漏电流 $I_{\text{loss, parallel}}=\frac{V}{R_p}$。
   并联电阻的功率损耗：
   $$P_{\text{loss, parallel}}=\frac{V^2}{R_p}$$
3. **总功率输出**：理想情况下，功率 $P_{\text{ideal}}=V_{OC}\cdot I_{SC}$。

题目要求总损耗小于1%，即：

$$P_{\text{loss, series}}+P_{\text{loss, parallel}}<0.01\cdot P_{\text{ideal}}$$

Q.8 A PV module is made up of 40 identical cells, all wired in series. With 1-sun insolation (1 kW/m²), each cell has short-circuit current I_{SC} = 4 A and at 25°C its reverse saturation current is $I_0=10^{-10}$ A. Parallel resistance R_P = 6 Ω and series resistance R_S =0.01Ω.

Find the voltage, current, and power delivered when the junction voltage of each cell is 0.60 V.

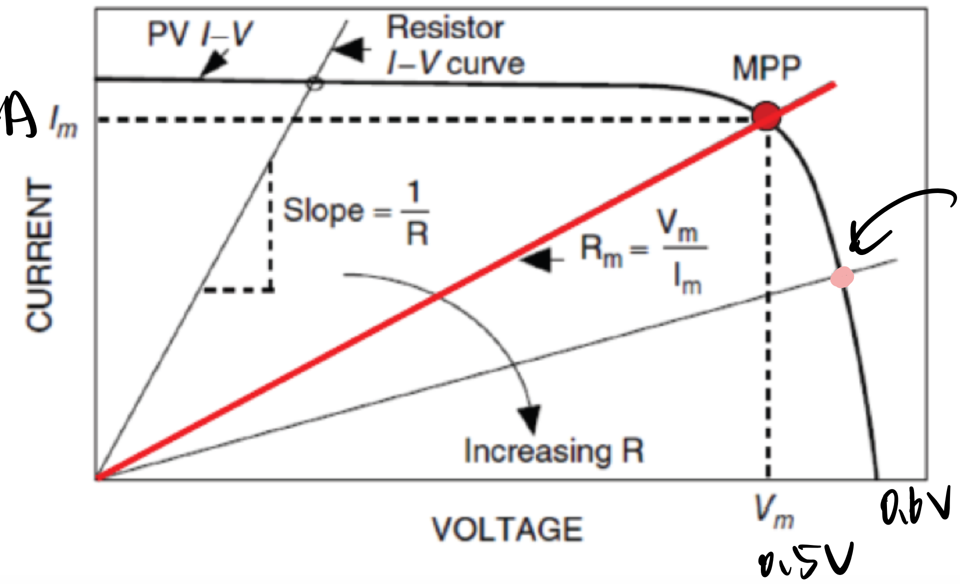
$n=40$ $I_{sc}=4A$ $I_0=10^{-10}A$ $R_p=6\Omega$ $R_s=0.01\Omega$ $V_d=0.6V$

$$I=I_{sc}-I_0(e^{38.9\times V_d}-1)-\frac{V_d}{R_p}=4-I_0(e^{23.34}-1)-\frac{0.6}{6}=2.53A$$

$$V=n(V_d-IR_s)=40(0.6-2.53\times0.01)=22.99V$$

$P=V\times I=58.16W$

Q.9 A PV cell output can be approximated to be linear from the maximum power point till the open circuit voltage. MPP voltage and current are: $V_p = 0.5$ V and $I_p = 4$ A. The open circuit voltage $V_{OC} = 0.6$ V. Determine operating point if a 1 Ω resistor is connected to the PV cell.



$R_p = \frac{V_p}{I_p} = \frac{0.5V}{4A} = 0.125\Omega$

Q10

Standard test conditions (STC)

- Solar irradiance – 1 kW/m² (sun)
- Air mass ratio of 1.5 AM
- Cell temperature 25°C

Q.11 How does solar insolation affect the short circuit current and open circuit voltage of the solar PV cells?

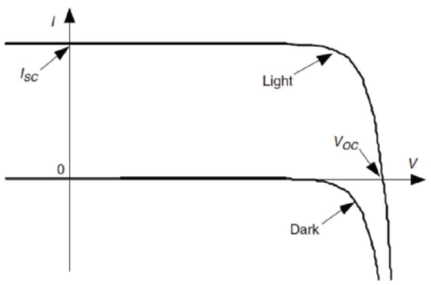
Q.12 Explain the effect of partial shading in solar PV modules? How is the effect mitigated in practical circuits?

11.

I-V characteristic of a Photovoltaic (PV) cell

$$\boxed{I = I_{SC} - I_0(e^{38.9\ V} - 1)}$$

$$\boxed{V_{OC} = 0.0257 \ln\left(\frac{I_{SC}}{I_0} + 1\right)}$$

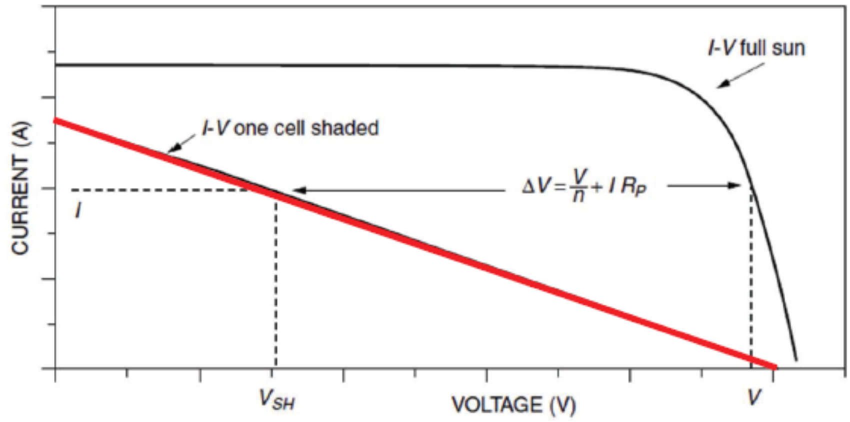


✓ Effect of Insolation

- As insolation drops, I_{SC} drops proportionately
- V_{OC} drops very slightly

Q.12 ① Effect of shading..

$$\Delta V \cong \frac{V}{n} + I R_P$$



② 1) Bypass Diode to mitigate effect of shading..

With bypass diodes, current is diverted around the shaded module.

2) Blocking Diodes

- For strings of modules connected in parallel, if one of the strings is not performing well, it tends to draw current
- Blocking diodes can prevent the reverse current drawn by shaded string

Q.13 A 40-cell PV module has a parallel resistance per cell of R_P =5 Ω where as the series resistance is R_s=0.01Ω. In full sun and at current I = 3 A the output voltage was found there to be V = 24 V. If one cell is shaded and the current somehow stays the same, then:

a. What would be the new module output voltage and power?

b. What would be the voltage drop across the shaded cell?

c. How much power would be dissipated in the shaded cell?

Q13 $n = 40$ $R_p = 5\Omega$ $R_s = 0.01\Omega$

full sun: $I = 3A \rightarrow V_{oc} = 24\,V$

one cell shaded $I = 3A$

a. new module output V and P

The drop in module voltage: $\Delta V = \frac{V}{n} + IR_p = \frac{24}{40} + 3 \times 5 = 15.6V$

$V = V_{oc} - \Delta V = 24 - 15.6 = 8.4V$

$P = VI = 8.4 \times 3A = 25.2W$

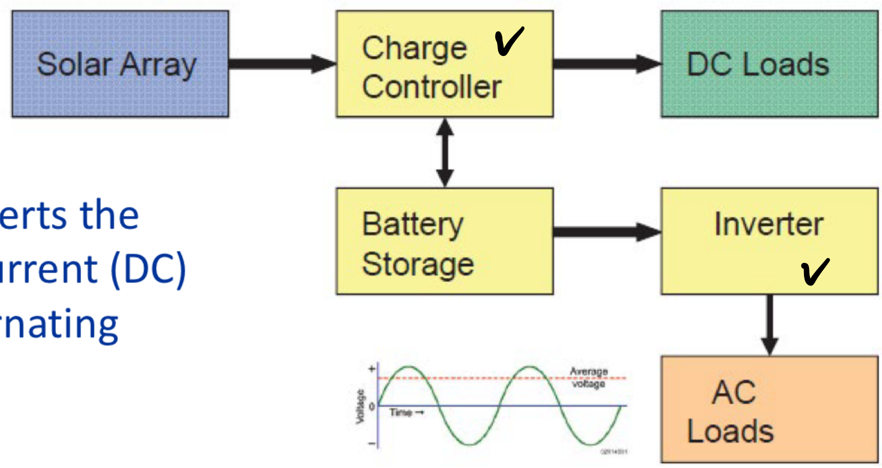
b. vol. drop

the drop across the shaded cell: $V_c = I(R_p + R_s) = 15.03\,W$

c. power dissipated 消耗 $P = V_c \cdot I = 15.03 \times 3 = 45.09W$

Q.14 Using block diagram show the components of a stand-alone Solar PV system for a remote home. Describe the function of various components.

Typical stand-alone system powering DC and AC loads:



- The inverter converts the system's direct-current (DC) electricity to alternating current (AC)
- Charge controller regulates the battery charging/discharge

Q.15 A remote home uses following appliances daily.

Appliance	Rating(W)	Daily usage duration (hours)
TV	100	10
Lights	50	12
Fan	100	20

Design the size of the solar PV panel and the battery capacity in Ah if the 12V battery is supposed to store energy for about 3 days. Assume that the battery can be discharged up to 80% of its storage capacity. The location has 5 peak-sun hours on an average. Assume full-sun insolation is $1 kW/m^2$.

Energy(wh/day) = $100 \times 10 + 50 \times 12 + 100 \times 20 = 3600$ wh/day

Energy (kwh/day) = 3.6 kwh/day

$$P_{ac} = \frac{3.6}{5} = 0.72 \text{ kW}$$

assume dc to ac = 75%

$$P_{dc} = \frac{0.72}{0.75} = 0.96 \text{ kW}$$

$P_{dc} = 1 \text{ kW/m}^2$ insolation $\cdot A(m^2) \cdot \eta$ assume $\eta = 12.5\%$

$$\therefore A = \frac{0.96 \text{ kW}}{1 \text{ kW/m}^2 \times 0.125} = 7.68 m^2$$

总电池容量 = $\frac{3600 wh \times 3}{0.8} = 13.5$ kwh

battery capacity = $\frac{13500 Wh}{12V}$

= 1125Ah

Q.16 What are the various causes for the losses in output power in a PV system?

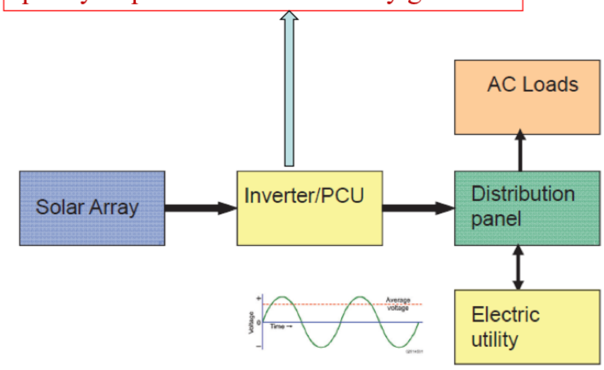
The conversion efficiency accounts for inverter efficiency, dirty collectors, mismatched modules, and differences in ambient conditions. Even in full sun, the impact of these losses can easily derate the power output by 20– 40%.

Q.17 Using detailed block diagram, show the components of a grid-connected solar PV system. Describe the function of each component.

Grid-connected PV Systems…

- The components of a grid-connected PV system include:
  - PV modules/arrays
  - An inverter and power conditioning unit (PCU)
  - A safety device to power down at failures in the grid and an electricity meter
- Designed to operate in parallel with, and interconnected with, the electric utility grid

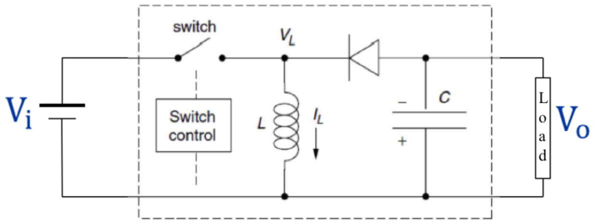
The primary component in grid-connected systems is the inverter/PCU which converts the DC power into AC power consistent with the voltage and power quality requirements of the utility grid



Q.18 Describe the operation of buck-boost converter used for MPPT operation in solar PV system.

Buck-Boost Converter operation

- When switch is CLOSED: energy supplied to inductor, and I_L builds up
- When switch is OPEN: Inductor current flows through C, load, and diode, and I_L decreases
- As the change in inductor current during two states of the switch, we can use *volt-sec balance of the*



Buck-boost converter

$$\Rightarrow V_o = \frac{D}{1-D} V_i$$

- The converter behaves as boost converter when $D > 0.5$.
- The converter behaves as buck converter when $D < 0.5$.

Q.19 Under certain ambient conditions, a PV module has its maximum power point at $V_m = 16$ V and $I_m = 4$ A. What duty cycle should an MPPT buck-boost converter have if the module is delivering the same power to a 1Ω resistance?

MPP : $V_m = 16V$ $\quad I_m = 4A$ $\longrightarrow 1\Omega \quad D = ?$

The max p delivered by PV is : $P = 16V \times 4A = 64W$

$$P = \frac{V_R^2}{R} = 64W$$

$$V_R = \sqrt{64 \times 1} = 8V$$

$\boxed{V_o = \frac{D}{1-D} V_i}$ $\quad 8 = \frac{D}{1-D} \times 16 \Rightarrow \frac{1}{2} = \frac{D}{1-D} \Rightarrow D = \frac{1}{3}$

Q.20 A PV panel under standard test conditions produces an output of 1000W. The output drops by 0.5%/^{0}C due to temperature rise and 5% due to dirt accumulation on it. The ambient temperature is 45^{0}C. Assuming power converter efficiency of 90%, determine the expected maximum AC power output from the panel.

$$P_{DC} = 1000\,[1 - 0.005(45-25)] = 1000 \times 0.9 = 900W$$

$$P_{AC} = 900 \times 0.95 \times 0.9 = 769.5W$$

Q.21 If a small remote community requires 1MWh/month, determine the area of standard solar PV panels required. State the assumptions made in your calculation.

1000 kwh / month 求 area.

Using data for singapore, 4.1 kwh/m²-day of annual insolation, using the peak hour approach.

$$\text{Energy (kWh/month)} = P_{ac}(\text{kW}) \cdot \frac{4.1}{\cancel{24}} \times 30 \times \cancel{24}$$

$$\Rightarrow P_{ac} = \frac{1000}{4.1 \times 30} = 8.13\,\text{kW}$$

assume 75% dc → ac.

$$P_{dc} = \frac{8.13}{0.75} = 10.84\,\text{kW}$$

To estimate the collector efficiency, $P_{dc} = 1\,\text{kW/m}^2\ \text{Insolation} \cdot A \cdot \eta$

assume $\eta = 12.5\%$.

$$A = \frac{10.84\,\text{kW}}{1\,\text{kW/m}^2 \times 0.125} = 86.72\,\text{m}^2$$

$$\text{Energy (kWh/yr)} = P_{ac}(\text{kW}) \cdot \text{CF} \cdot \overset{365 \times 24}{8760}(\text{h/yr})$$

$$\text{Energy (kWh/day)} = P_{ac}(\text{kW}) \cdot (\text{h/day of “peak sun”})$$

$$\text{Capacity factor (CF)} = \frac{(\text{h/day of “peak sun”})}{24\ \text{h/day}}$$