4B19 2018 crib Dr T J Flack Prof G A J Amaratunga

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1 a) Advantages: higher mean wind speeds so greater power for given turbine size

: less planning restrictions

: wind more consistent so greater capacity factor

Disadvantages: Cost of installation and getting power ashore

: Harder & costlier to maintain

: Longer outages following a failure.

b) DC links solve a variety of problems: line-line capacitance of 3ϕ cable creates a lot of generated Q because cables are in close proximity. This does not happen with DC link since $\omega = 0$. Copper utilisation better (no skin effect). Power $\sqrt{2}$ higher because peak voltage = DC voltage not $\sqrt{2} \times$ rms voltage

If a DC link is used, all generator o/p power must be converted to DC. Therefore PMG changes in voltage amplitude and frequency with wind speed don't matter. They offer high reliability and lower losses than DFIG, plus have high power density at low rpm.

c) i) $P = \frac{1}{2} C_p \rho A v^3$

$= \frac{1}{2} \times 0.42 \times 1.23 \times \pi \times 45^2 \times 12^3 = \underline{2.83\ MW} = P_{rated}$

$\lambda = \frac{\omega R}{v}$ $\quad 9 = \frac{\omega \times 45}{12}$ $\quad \underline{\omega = 2.4\ rad\,s^{-1}}$ at rated wind speed.

$T\omega = P_{rated} \Rightarrow \underline{T = 1.18\ MNm}$

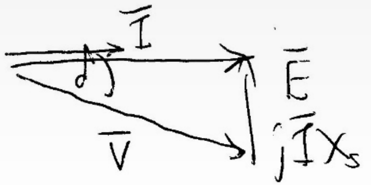
ii) $E_{ph} = k\omega_r = 320 \times 2.4 = 768V$ so $\sqrt{3} \times 768 = \underline{1.33kV\ line}$

$P = 3 E_{ph} I_{ph} \Rightarrow 2.83 \times 10^6 = 3 \times 768 \times I$

$\underline{I = 1228A}$

$\omega_s = \frac{\omega}{p}$ $\quad p = 24 \Rightarrow \omega = 24 \times 2.4 = 57.6\ rad\,s^{-1}$

$\bar{E} = \bar{V} + j\bar{I}X_s$ $\qquad X_s = \omega L_s = 0.0576\Omega$



$$V^2 = E^2 + (X_s I)^2 = 768^2 + (0.0576 \times 1228)^2$$

so $V_{ph} = 771\,V = \underline{1336\ V\ \text{line}}$

$\delta = \tan^{-1} \frac{IX_s}{E} = \tan^{-1} \frac{1228 \times 0.0576}{768} = \underline{5.26°}$

d) Assume generator output power $\propto v^3$ for $v < v_{rated}$

$v = 6\,ms^{-1}$ $P = \left(\frac{6}{12}\right)^3 \times 2.83 = 354$ kW per turbine

Power to DC link $= \eta \times 354 \times 80 = 0.95 \times 354 \times 80 = 26.9$ MW

± 180kV means $V_{DC} = 360$ kV and $P = V_{DC} I_{DC}$

so $26.9 \times 10^6 = 360 \times 10^3 I_{DC}$ $\underline{I_{DC} = 74.7A}$

$v = 10\,ms^{-1}$: $P = \left(\frac{10}{12}\right)^3 \times 2.83 = 1.64$ MW per turbine.

$\therefore 0.95 \times 1.64 \times 10^6 \times 80 = 360 \times 10^3 I_{DC}$ $\underline{I_{DC} = 346A}$

$v = 14\,ms^{-1}$: $P = P_{rated} = 2.83$ MW

$\therefore 0.95 \times 2.83 \times 10^6 \times 80 = 360 \times 10^3 I_{DC}$ $\underline{I_{DC} = 597A}$

2/ a) P.E. stored in water of mass M at height H above turbine is $MgH = \rho V g H$

$$\text{Power} = \frac{d}{dt}(P.E.) = \rho g H \frac{dV}{dt} = \rho g H Q$$

where Q = volumetric flow rate.

This is an upper limit, take account of power loss by efficiency η

$$\therefore P = \eta \rho g H Q$$

Typical generator speed for hydro applications is of the order of a few hundred rpm. Desirable to connect directly to 50 Hz grid, and since $N_s = \frac{60 f}{p}$, N°. of pole-pairs p must be large. ∴ Salient-pole synchronous generator is used.

b) Pumped storage: uses off-peak electricity to pump water from lower to upper reservoir, at periods of peak demand system operates as a turbine-generator. ∴ Can regard pumped storage as a large store of energy that can be converted to electricity very quickly to meet peak demand.

Because renewables are generally intermittent this form of energy storage means that more renewable sources can be integrated, as gaps in generation from such sources can be met from stored energy.

DCF is a method that releases future income/expenditure to a common point in time, enabling the cost/kWh at present to be evaluated. This can then be compared to other forms of generation. It means that the cost of borrowing to invest is accounted for. However, it assumes all capital is expended at the start of the project. This is reasonable for some renewables e.g. solar PV, but a pumped storage scheme would take many years to become operational.

c) $H = 300\,m$, $P = 200\,MW$, $\eta = 0.75$. High head of water means that impulse turbines used (Francis for medium head & propeller for low head).

Using $P = \eta \rho g H Q$ $\quad 200 \times 10^6 = 0.75 \times 1000 \times 9.81 \times 300 Q$

giving $\underline{Q = 90.6\ m^3 s^{-1}}$

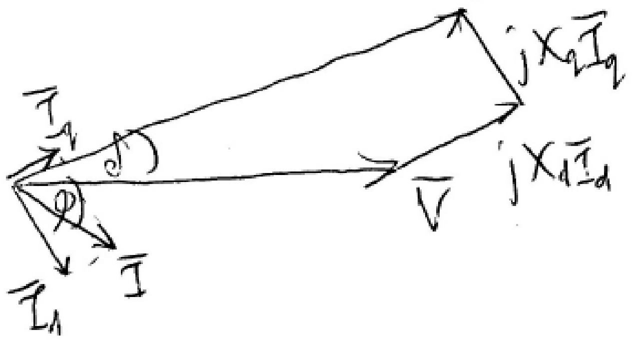
d) (i) Assume total scheme power shared equally $\therefore P = 25\,MW$

$$\omega_s = \frac{2\pi f}{p} = \frac{2\pi \times 50}{5} = 62.8\ \text{rad s}^{-1} \quad (600\ \text{rpm})$$

$$T\omega_s = 25 \times 10^6 \Rightarrow \underline{T = 398\ \text{kNm}}$$

$$3 V_{ph} I_{ph} \cos\phi = 25 \times 10^6 \Rightarrow I_{ph} = \underline{3645\,A}$$

ii)



$$I_q = I\cos(\phi + \delta)$$

$$V\sin\delta = X_q I_q = X_q I(\cos\phi\cos\delta - \sin\phi\sin\delta)$$

$$\sin\delta\,(V + X_q I\sin\phi) = X_q I\cos\phi\cos\delta$$

$$\tan\delta = \frac{X_q I\cos\phi}{V + X_q I\sin\phi}$$

iii) $\cos\phi = 0.6$, $\sin\phi = 0.8$, $X_q = 0.6\,\Omega$

$$P = 3V_{ph}I_{ph}\cos\phi = 25\times10^6 \quad V_{ph} = \frac{6.6\,kV}{\sqrt{3}} = 3.81\,kV$$

$$3\times3810\times I_{ph}\times0.6 = 25\times10^6$$

$I_{ph} = 3645\,A$

$$\tan\delta = \frac{0.6\times3645\times0.6}{3810 + 0.6\times3645\times0.8} = 0.236$$

$\delta = 13.3^\circ$

$\phi = \cos^{-1}0.6 = 53.1^\circ$ so $\phi+\delta = 66.4^\circ$

$I_q = I\cos(\phi+\delta) = 1460\,A$

$I_d = I\sin(\phi+\delta) = 3340\,A$

$$E = V\cos\delta + X_d I_d = 3810\cos13.3^\circ + 0.8\times3340$$

$= 6380\,V = 11.05\,kV$ line

Answers

Q3

a) i) Built in potential

$$V_{bi} = \frac{KT}{q} \ln\left[\frac{N_D N_A}{n_i^2}\right]$$

$$= \frac{1.38\times10^{-23}\times300}{1.60\times10^{-19}} \ln\left[\frac{5\times10^{46}}{25\times10^{32}}\right]$$

$$= 0.026 \ln\left[0.2\times10^{14}\right]$$

$$= 0.80\,V$$

ii)

$$I_S = qA\left[\frac{n_i^2}{N_D}\frac{L_h}{\tau_h} + \frac{n_i^2}{N_A}\frac{L_e}{\tau_e}\right]$$

Since $N_D >> N_A$ and $\frac{L_h}{\tau_h}, \frac{L_e}{\tau_e}$ same order

$$I_S \simeq qA\left[\frac{25\times10^{32}}{5\times10^{22}} \times \frac{50\times10^{-6}}{10\times10^{-6}}\right]$$

$$\simeq qA\left[2.5\times10^{10}\right] = 1.602\times10^{-19}\times10^{-2}\times25\times10^{10}$$

$$\simeq 4\times10^{-10} \simeq 400\,pA$$

b)

Bi)

$$V_{oc} = \frac{kT}{q} \ln\left[\frac{I_{sc}}{I_{s}}+1\right]$$

where I_{sc} = short circuit current

$$\therefore \quad I_{sc} = I_s \times \exp\left(\frac{q \cdot V_{oc}}{kT}\right)$$

$$= 4\times10^{-10} \exp\left(\frac{0.6}{0.026}\right) = ~~0.42A~~ \; 4.2A$$

ii) Solar input power = $1\,kW\,m^{-2}$

$\therefore$ power into cell = $1\times10^3 \times 10^{-2} = 10W$

solar cell efficiency = $\frac{V_{oc} I_{sc} FF}{\text{input power}}$

FF = Fill factor. This is an empirical formula given in the supplementary Formulae and Constants sheet.

$$FF_0 = \frac{v_0 - \ln(v_0 + 0.72)}{v_0 + 1}$$

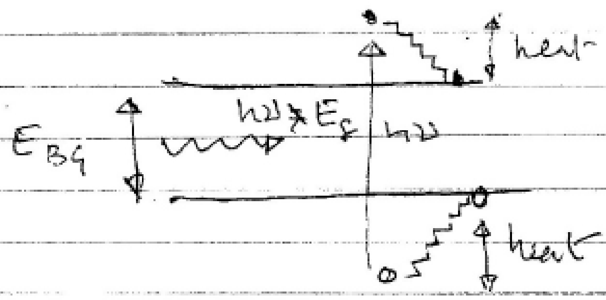
$$v_0 = \frac{qV_{oc}}{kT} = \frac{0.6}{0.026} = 23.08$$

$$FF_1 = \frac{23.08 - \ln[23.08 + 0.72]}{24.08}$$

$$= 0.83$$

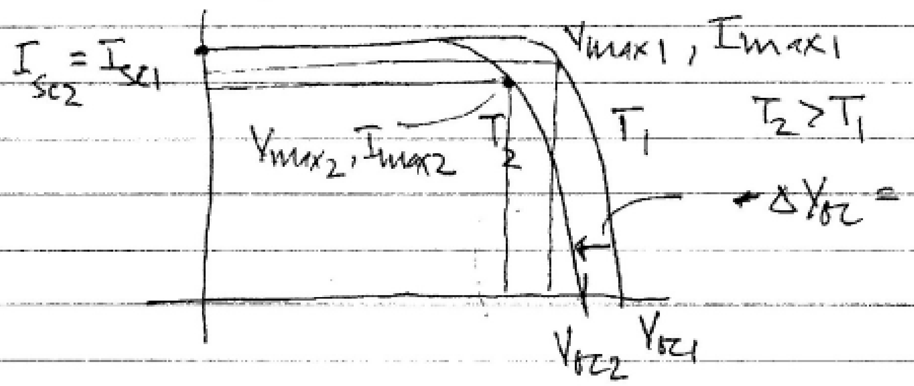
$$\therefore \eta = \frac{0.6 \times 4.2 \times 0.83}{10} = 20.9\%$$

iiii) When a photon with energy above the band-gap energy is absorbed the difference in energy has to be dissipated as heat. i.e. the electron hole pair generated can only be extracted at the band gap energy at most. But even this energy is not available in practice as $V_{OC} < V_{BG}$.



Therefore the Solar Cell in operation will get hot and be above the ambient (dark) temperature. It has to be in equilibrium with the environment, this means it will ~~get~~ have a temperature above ambient which allows it to maintain a radiative heat flux out of it which is equal to the heat dissipated by the absorbed photons.

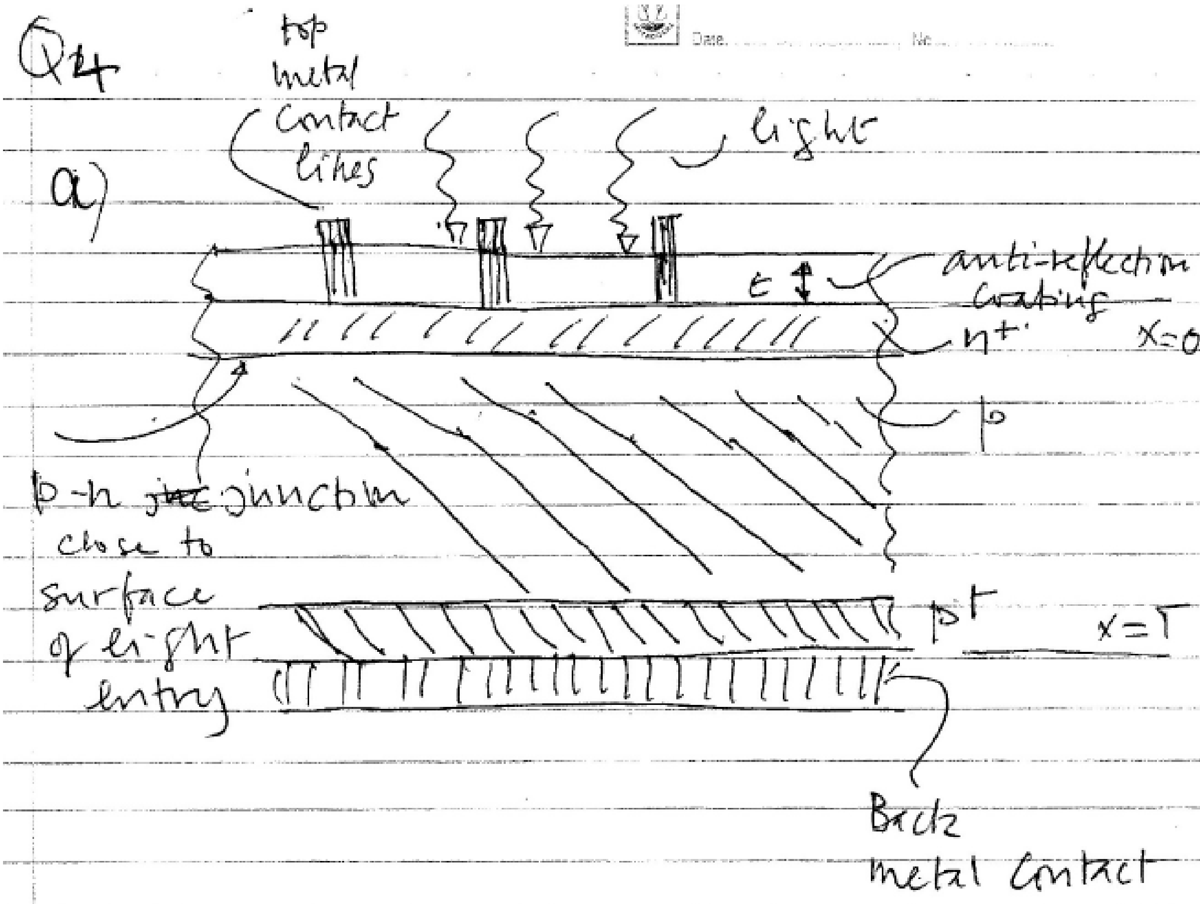
If temperature rises then n_i will rise. This leads to I_s rising. The rise in n_i is exponential and I_s rises even faster as $I_s \propto n_i^2$. The nett effect is for V_{oc} to drop and hence efficiency will also drop. Also this has the effect of reducing FF.



$$\frac{V_{max} I_{max}}{V_{oc} I_{sc}} = FF$$

Q4

a)



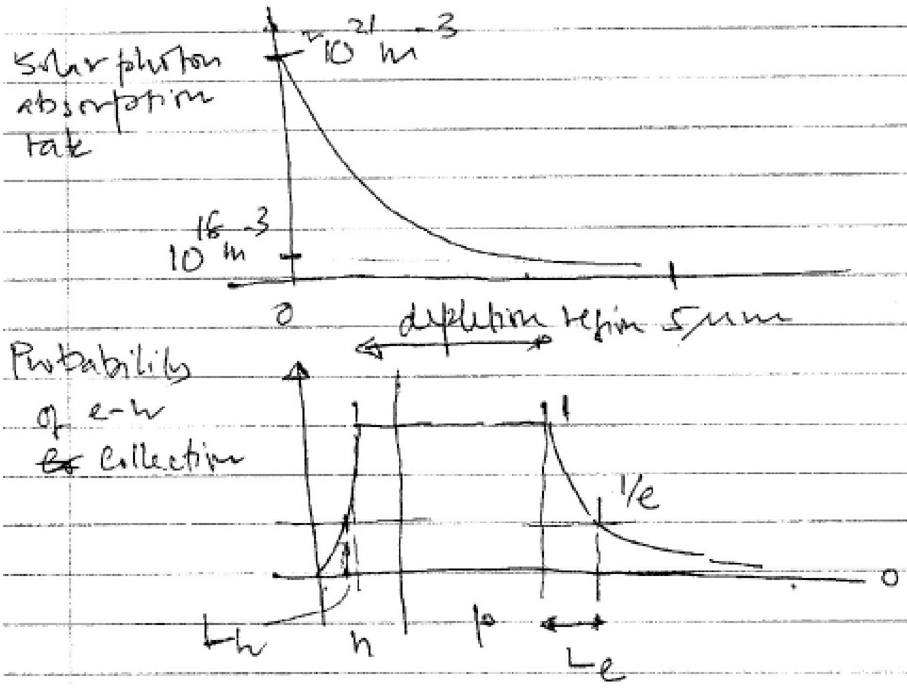
b) Light absorption in Si follows the electromagnetic wave decay characteristics in a metal for all energies above the band-gap.

$I = I_0 \exp(-\alpha x)$ where I_0 is light intensity entering the cell at $x=0$

This means the absorbed light decays exponentially with distance into the cell. Most of the solar spectrum is well above the band-gap energy of Si (1.1eV ~1000nm) and is absorbed close to the surface within 1-5 μm

Q4 Answers

The probability of separating a photon generated electron-hole pair to generated a photo current and voltage in turn decays exponentially away from the depletion edge of the p-n junction. Therefore the junction has to be placed close to the surface where most of the solar spectrum is absorbed



This requires the junction to be placed close to the surface.

However, this then poses the problem of electrons in the n-layer having to travel laterally in a thin resistive region to the

Q4 Answers

i) From the formulae and constants sheet

R is minimised to

$$R = \frac{(n_1 n_3 - n_2^2)}{(n_1 n_3 + n_2^2)} \quad \text{when } \theta = \pi/2$$

where n_1, n_2 and n_3 are the refractive indices of air anti-reflection coating and Si respectively.

$$\therefore \ \pi/2 = \frac{2\pi 2 d}{550}$$

$$d = 550/8 \ \text{nm} = 58.75 \ \text{nm}$$

$$\simeq 60 \ \text{nm}$$

This gives $R(550\text{nm}) = \frac{(\sqrt{11.9} - 4)}{(\sqrt{11.9} + 4)} \simeq 0.07$

ii) $R = 0$ when $n_2 = \sqrt{n_3} = \sqrt{3.45}$

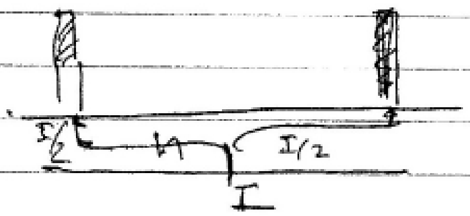
$$= 1.86$$

iii) and $d = \frac{550}{4 \times 1.86} = 43.93 \ \text{nm}$

$$\simeq 44 \ \text{nm}$$

Q2 Answers

contacts.

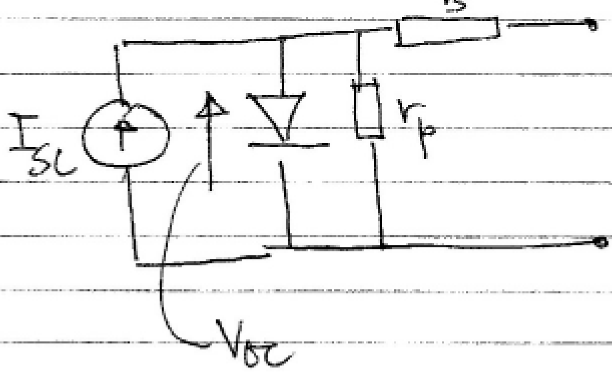


To alleviate this problem the n-layer is heavily doped to reduce its resistance. But this leads to the effective depletion region on the n-side and the corresponding collection region (for holes) to drastically reduced. Therefore the Si p-n junction solar cell in effect operates as a n^+p junction with most of the photo-generated carriers being electrons (minority) carriers in the p side which get swept across the junction to the n-side and holes generated on the p side which are collected at the back contact.

The overall thickness of the cell T is chosen to maximise absorption of the long wavelength (near band-gap energy) photons.

Q4 Answers.

d) The antireflection coating enhances light coupled into the cell. More light in the cell (specially at the peak of the solar spectrum at ~550nm) will lead to more absorption and electron-hole pair generation. This is reflected in a higher I_{sc}.



I_{sc} is enhanced by having an anti-reflection coating. i.e. I_{sc} increases

Q1 Offshore wind

Very popular question, attempted by many candidates and generally very well answered. A common error was to find the synchronous speed of a permanent magnet generator as if it was connected directly to a 50 Hz grid, whereas the speed is dictated by the turbine. Some students took the DC link voltage to be 180 kV instead of 360 kV.

Q2 Hydroelectricity and salient pole synchronous machines

A popular questions with generally excellent answers to the first three sections. Part (d) on salient pole generators polarised the candidates into those who understood these machines and those who didn't.

Q3 Solar PV – Semiconductor fundamentals of the solar cell

A very popular question attempted by 80% of candidates on the principles of the p-n junction and its operation as a solar cell to generate power. Nearly all those answering understood the operation of the junction and its exploitation in the reverse conducting mode under solar illumination to act as a cell. The resulting solar cell parameters of short circuit current, efficiency and the impact of temperature were all well understood

Q4 Solar PV – Optical design of the solar cell

The question addressed the design issues and parameters involved in maximizing the light coupled into a p-n junction Si solar cell. Those answering the question had a good grasp of the main design tradeoffs and the significance of having an anti-reflection coating.