4B19 2019 Crib Saikat Ghosh and Gehan Amaratunga

1 (a)

Energy potential - wind data is gathered, usually measured over a year or more, to make an accurate
assessment of the site.
Engineering considerations - suitability of the site for structure; ease of connecting to the grid, particularly offshore; strength of the grid.
Logistics - transporting and constructing the wind turbine
Social - planning; noise; distraction of road users.
Environmental - visual impairment of landscape; bird strike; damage to other flora/fauna/ecosystems
Risk to aviation and shipping (offshore).
Economic - payback time; cost of electricity generated Ease and cost of ongoing maintenance

1(b)

The slip energy recovery also known as doubly fed induction generator (DFIG) enables variable speed operation which in turn maximises the power extracted from the wind at all wind speeds between cut-in and rated. The DFIG utilises a fractionally rated power electronic converter (PEC) as opposed to processing all the output power. The PEC can be operated such that the DFIG can generate reactive power. The PEC enables 3-phase voltages to be fed into the rotor slip rings at a variety of magnitudes, frequencies and phases. By adjusting the frequency, the rotor speed may be varied since doing this directly controls the DFIG slip. Hence, the torque-speed characteristic of the DFIG can be shifted so that the no-load speed is less than or greater than synchronous speed, whilst preserving a steep torque-speed characteristic around the no-load speed.

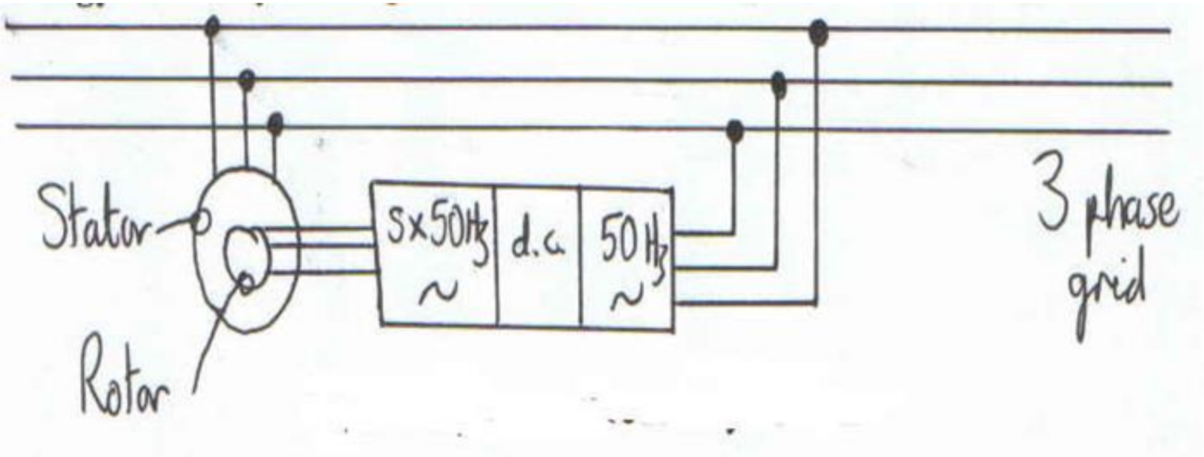


Figure 1 Slip Energy Recovery Scheme

1.(c)

Maximum power $=$ 2.5 MW

Differentiating Eqn for C_p, $-0.01\lambda + 0.08 = 0 \Rightarrow \lambda = 8$

maximum $C_p = 0.4$, at $\lambda = 8$;

Most probable speed $=$ 14m/s

$P = 0.5\rho C_p A v^3$

$2.5 \times 10^6 = 0.5 \times 1.14 \times 0.4 \times A \times 14^3$

$\Rightarrow A = 3996m^3 \Rightarrow \pi R^2 = 3996 \Rightarrow R = 35.66m$

Considering cut in speed and stall speed the following table can be prepared for power and energy calculation:

Table 1: Power and Energy Calculation Table

Wind Speed	Days	$\lambda = \frac{\lambda_{opt} \times v_{most}}{v}$	C_p	C_p	Power	Actual Power	Hours	Energy
(m/s)				[Cut in /Stall]	[in MW]	[Rated power limit]		[in GWhr]
3	25	37.33	0	0	0	0	600	0
8	45	14	0.22	0.22	0.26	0.26	1080	0.28
10	90	11.2	0.35	0.35	0.79	0.79	2160	1.72
14	120	8	0.4	0.4	2.5	2.5	2880	7.2
18	50	6.22	0.38	0.38	5.1	2.5	1200	3.0
21	25	5.33	0.36	0	0	0	600	0
24	10	4.67	0.34	0	0	0	240	0
Total	365							12.2

Hence total **12.2GWhr** energy is supplied by the plant.

The utilization factor is given as $\frac{12.2 \times 10^3}{2.5 \times 365 \times 24} = 55.7\%$

1.(d)

Capital cost of the plant $=$ £ $2.5 \times 10^3 \times 1500 =$ £ 3750000

Maintenance cost (a)$=$ £ 150000

Actual interest rate $= 5\%$

From the annuitisation table for 5% payment over 25 year period capital repayment $=$ £71 per year per £ 1000.

Annual payment (b)$=$ £ 266250

Total cost $=$ a$+$b $=$ £ 416250

Total electricity produced $=$ 12.2 GWhr

Electricity cost $= \frac{416250}{12.2 \times 10^6} £/kWhr = 3.4$ p/kWhr

Annual profit $= (10.6 - 3.34) \times 12.2 \times 10^6 =$ £ 876223

Assessor's comment:

Majority of the students attempted this question, and generally well answered. A common mistake was not limiting the output power to 2.5 Mw for 18m/s in 1c. A few students made mistake in the (1d), in calculation of the annual payment for the borrowed capital from the annuitisation table, by taking the payment as 1071£/yr.

2.a.
AC sub-sea cables has the following problems:
- skin effect at AC exacerbates heat production
- three phases are in proximity giving high capacitance - leading to problems with reactive power

Whereas DC subsea cables has the following advantages
- no capacitive/inductive reactance
- control of DC power flow easier - current flows over whole cross section of cable

Hence long-distance offshore wind farms connection to the grid is usually accomplished by HVDC.

2.b.
a. Advantages:
i. Hydroelectric power is clean and renewable and does not involve the burning of fossil fuels. The process of generating power does not produce greenhouse gases that contribute to climate change.

ii. Hydroelectric schemes are powered by the hydrological cycle and as such does not rely on a resource that is limited (on an engineering time scale anyway).

iii. Hydroelectric schemes have existed since ancient times and it is a well-understood and well-developed process.

iv. The cost of power generated by hydroelectric schemes is very cheap once the infrastructure is installed.

v. Hydroelectric power plants often have long lifetimes, and operating costs are usually low with automated processes and a minimal human presence required during normal operation.

b. Disadvantages:
i. Most good (and economical) sites have already been developed in developed countries, particularly the UK

ii. Environmental issues such as ecosystem damage and loss of land. Hydroelectric schemes can affect ecosystems and wildlife both up- and down-stream of the plant.

iii. It usually takes a long time for the construction requiring heavy capital investment without return in initial period, thus making less attractive option from the economic perspective

2.c. Water of mass M stored at a height H with respect to the point where the energy is extracted has potential energy, $PE = MgH$

When water is released the rate at which energy is extracted (i.e., the power) is given by $P = d(MgH)/dt = gHdM/dt = gH\rho dV/dt = \rho gHQ$ where ρ is the density of water, g is the acceleration due to gravity, H is the height of the water (or the 'head') and Q is the volumetric flow rate in m^3/s.

However, losses mean that not all of this power is extracted, and this is accounted for by the efficiency term η giving $P = \eta\rho gHQ$

Hydroelectric schemes are characterised as : high head (H $>$ 100 m), low head (H $<$ 10 m) or medium head (10 m $<$ H $<$ 100 m). Low head = Propeller turbine, medium head = Francis turbine, high head = Impulse turbine.

2d.

(i)

50Hz frequency, 300RPM speed; The number of pole pair p given as:

$p = \frac{50\times60}{300}$=10; Hence 20 poles machine.

100MW plant, 80% turbine efficiency ; Active power input (P) given as:

$P = 100 \times 0.8 = 80MW$;

Torque = $\frac{P}{\omega} = \frac{80\times10^6}{(\frac{300\times2\pi}{60})}$ = 2546 kNm

Reactive power Q = 60MVAr

Apparent Power S = $\sqrt{P^2+Q^2}$ = 100MVA;

$\sqrt{3}V_lI_l = 100 \times 10^6 \Rightarrow I_l$= 1750A; [$V_l$=33kV]

Power factor = P/S = 0.8 (lagging)

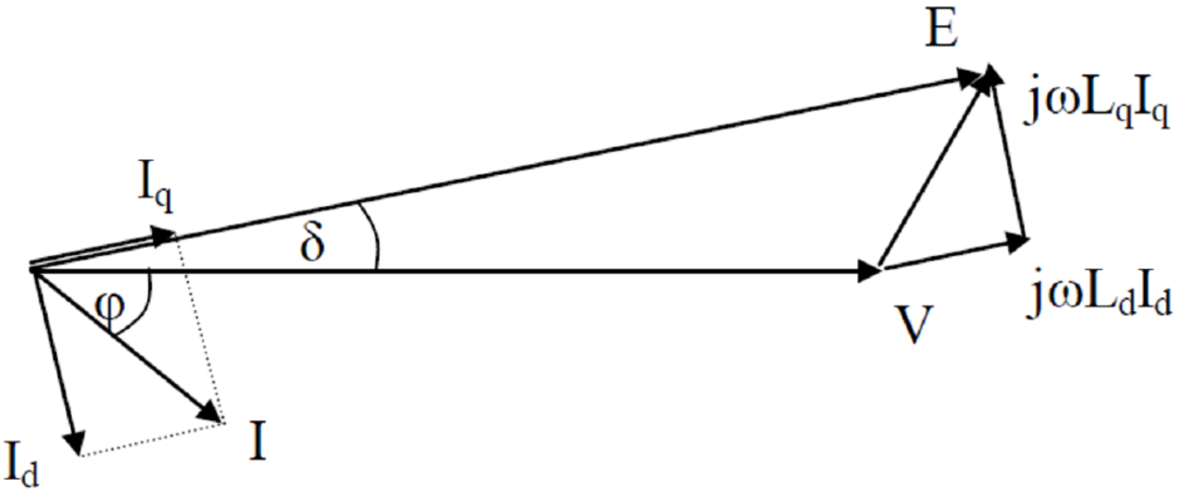


Figure 2: Phasor Diagram

$E = V + jX_dI_d + jX_qI_q$; Such that $I = I_d + I_q$

$P_{out} = 3VI\cos\phi$

$I\cos\phi = I_d\sin\delta + I_q\cos\delta$

$I_dX_d = E - V cos\delta$

$I_qX_q = V\sin\delta$

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

$V\sin\delta = X_qI(\cos\phi cos\delta - \sin\phi\sin\delta)$

Dividing by $\cos\delta$

$\tan\delta = \frac{X_qI\cos\phi}{V+X_qI\sin\phi}$ =0.18 $\Rightarrow \delta = 10.23^o$

$I_d = I\sin(\phi+\delta) = 1282A$

$E = V\cos\delta + I_dX_d$ = 41.4kV

Assessor's comment:

A very popular question and in general well answered. Majority of the student got the phasor diagram in (2d) correct. However, some of the students made mistake at the last part in the derivation of tan δ. A common mistake was not converting the excitation (E) in the line voltage from the phase voltage calculation.

Q3

(a) (i)

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

$n_i = 3.18 \times 10^{16}$ at T = 300 K from expression given. N_D (n- doping), N_A (p-doping) defined in Q and K, q from data book or formulae and constants sheet

$$V_{bi} = 0.026\ln\left[\frac{10^{48}}{10.1^{32}}\right] = 0.90\,V$$

(ii)

$$I_s = qA\left[\frac{n_i^2 D_e}{N_A L_e} + \frac{n_i^2 D_h}{N_D L_h}\right] \quad and\ L_{e,h} = \sqrt{D_{e,h} t_{e,h}}$$

D_e and D_h diffusion length for electrons (minority carries in the p-region) and holes (minority carriers in the n-region) and t_e and t_h their respective lifetimes. A junction area.

Plugging in values on gets $I_s = 6.48 \times 10^{-12}$ A

(iii)

$$V_{turn\ on} = \frac{KT}{q}\ln\left[\frac{I}{I_s} + 1\right]$$

$I = 10^{-2}$, all other parameters known and calculated in (ii)

$$V_{turn\ on} = 0.55\,V$$

(b) (i) The short circuit current is equal to the optically generated current.

$$I_{SC} = I_{OP} = qAg[L_e + L_h]$$

g is the generation rate defined in the Q, A junction area , L_e= 40 μm and L_h = 1μm from the parameters for $D_{e,h}$ and $t_{e,h}$ given.

$$I_{OP} = 3.94\,A$$

(ii) As T has changed to 340K n_i changes and hence I_s also changes to:

$$n_i = 4.76 \times 10^{17}\ cm^{-3}\ and\ I_S = 1.45 \times 10^{-9}\ A$$

$$V_{open\ circuit} = \frac{KT}{q}\ln\left[\frac{I_{SC}}{I_s} + 1\right] = 0.64\,V - note\ T = 340\ K$$

(iii) The new built in voltage is

$$V_{bi} = 0.029\ln\left[\frac{10^{48}}{19.89^{34}}\right] = 0.84\,V$$

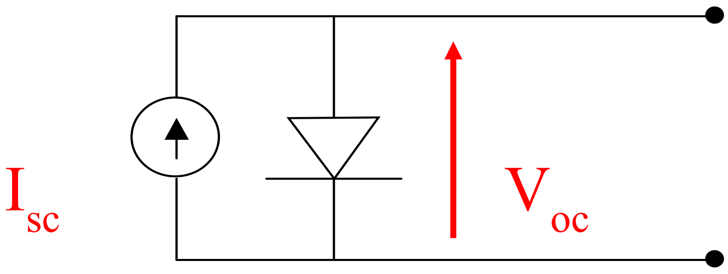
The corresponding open circuit voltage from (v) is 0.64 V. The built in voltage is the voltage which would be applied to make the band across the junction flat. But before the band become flat, with reduction of the potential barrier to minority current flow, current starts to flow as carriers can be thermally excited over the barrier (gain voltage KT/q). Hence the open circuit voltage is lower.

Assessor's comments

A question on the fundamental semiconductor properties of a p-n junction and how they apply to a solar cell. The question was more popular amongst the graduate student candidates. The answers were binary in terms of quality, with some achieving near full marks and others achieving pass marks.

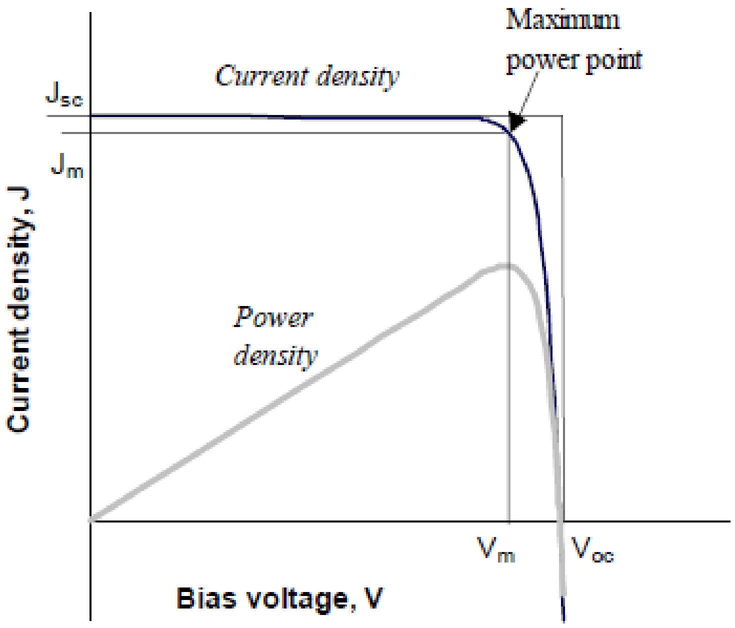
Q4

(a) The equivalent circuit for an ideal solar cell only considers the junction characteristics. It is given as



The current source represents the short circuit current of the cell. Under open circuit all the short-circuit current passes through the forward biased diode which in effect is the internal impedance of the current source. So we have a very low impedance current source, as opposed to a current source which would have very high (ideally infinite) internal impedance. Additionally the internal impedance, as it is a diode , is non-linear.

(b) As the internal impedance in the equivalent circuit is non-linear it is not possible to analytically predict what the maximum power is. To do this we use an empirical/graphical method.



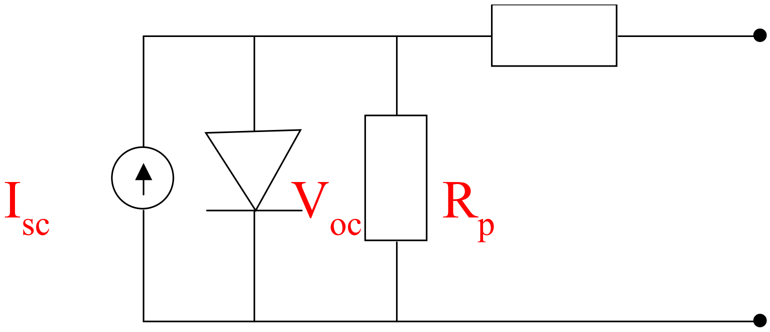
The measured maximum power point in volts and amps (J× junction area) is taken as a ratio of the nominal reference power $V_{OC}\times J_{SC}.A$.

$FF_0 = \frac{V_{max}I_{max}}{V_{OC}I_{SC}}$ hence $P_{max} = FF_0 V_{oc} I_{SC}$

There is an empirical expression for FF_0 as a function of V_{OC} and T for Si which has been derived (as in Formulae sheet).

(c) A practical solar cell is not only the junction. There are series resistances with junction due to the bulk Si across which the photogenerated current flows to the terminals. Additionally there is always resistance between the Si and the metal contacts (contact resistance) which is also in series (generally both are lumped together in a single resistance). Additionally there can be a leakage resistance parallel to the diode, takes current out from the main current, due to damage at the perimeter edges of the cell. If the area/perimeter ratio is very high then this parallel resistance can be take to approach infinity.

The modified equivalent circuit is:



(d)(i)

Use the formula given in the Formulae and Constants Sheet

$$FF_o = \frac{\frac{qV_{oc}}{kT} - ln\left(\frac{qV_{oc}}{kT} + 0.72\right)}{\frac{qV_{oc}}{kT} + 1}$$

$qV_{oc}/KT = 0.6/0.029 = 21$ and $FF_0 = 0.81$

(ii)

$$V_{OC} = I(r + R_L)$$

$$I^2 R_L = 6.25 \times 200 \times 10^{-3} = \ 1.25\ W$$

The efficiency at this operating point is therefore 1.25/10 = 12.5%

(d)(iii) The internal resistance (taken to be the contact resistance) from 2 is given as

$r = \frac{0.6}{2.5} - 0.2 = 40\ \text{m}\ \Omega$

The modified Fill Factor $FF_1 = FF_0\left(1 - \frac{r}{r_0}\right)$ therefore $r_0 = \frac{r}{\left(1 - \frac{FF_1}{FF_0}\right)} = \frac{0.04}{0.203} = 0.197$

$r_0 = \frac{V_{OC}}{I_{SC}}$ and $I_{SC} = \frac{0.6}{0.197} = 3.1\ A$

(d)(iv)

Expected maximum efficiency is at maximum power.

Efficiency = $\frac{0.65 \times 0.6 \times 3.1}{10} = 0.124 = 12.4\%$

Worth noting that even a very small contact resistance of 40 mΩ has a significant effect on the maximum efficiency as the internal resistance of the current source is very low and hence the load resistance has also got to be of the same order to draw significant power.

Assessor's comments

A question based on the equivalent circuit for a Si solar cell and calculating efficiencies and performance parameters based on it. This was the more popular question amongst the Part IIB candidates. In general the question was well answered with approximately 10 – 15% completing the question fully and correctly.