4B19 2013 crib

1. (a) Any two of:

No brushes, so more reliable/easy to maintain.

High torque and power outputs available at low speeds, so no gearbox required.

High power density because of modern permanent magnet materials.

Equivalent circuit and phasor diagram are shown below, Fig 1. and Fig 2 respectively.

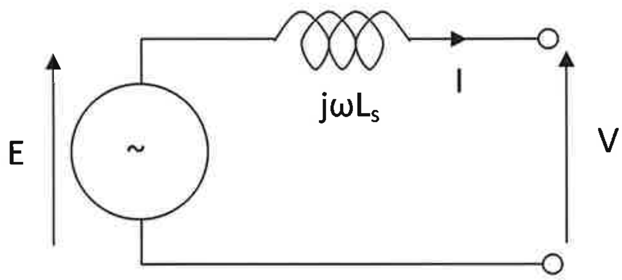

Fig. 1

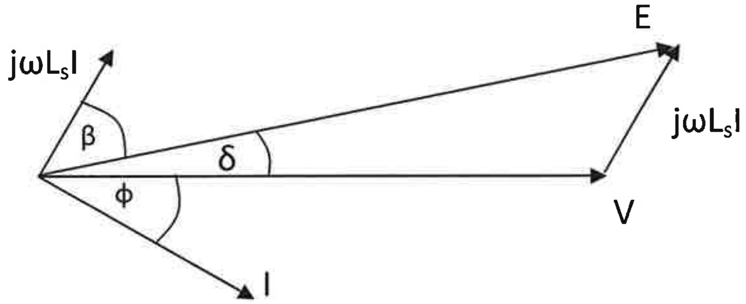

Fig. 2

Starting from data book expression for the torque of a synchronous machine:

$T_e = 3VE\sin\delta/\omega_s X_s$

and noting that $E = k\omega_s$ and $V\sin\delta = X_s I\sin\beta$, gives $T = 3kI\sin\beta$. Therefore, at fixed torque angle β the torque is proportional to the phase current, as required.

For maximum torque per amp $\sin\beta$ should be 1, so $\beta = 90$ degrees. [25%]

(b) (i) Using $P = 0.5C_p\rho Av^3$ and substituting in P=10 kW, C_p=0.35, ρ=1.23 kgm^{-3} and v=12ms^{-1} gives the swept area A = 26.9 m^2.

Equating this with $\pi d^2/4$ gives d = 5.85 m.

(ii) At the 8 ms^{-1} wind speed, and noting that power is proportional to v^3, the input power to the PMG is $(8/12)^3 \times 10$ kW = 2.96 kW.

Using $\lambda=\omega R/v$, and substituting in v=8 ms^{-1}, R=5.85/2 m and λ=9, gives the turbine angular speed ω_s = 24.6 $rads^{-1}$.

Using $P=T\omega_s$ gives the input torque T=120 Nm.

Assuming that the torque angle is maintained at 90° then T=3kI giving I=12.5 A

The PMG is an 8 pole generator, so p=4, giving $\omega=p\omega_s$=98.4 $rads^{-1}$, from which the synchronous reactance may be found as $X_s=\omega L_s$=0.492 Ω. At a torque angle of 90^0:

$V^2=E^2+(X_sI)^2$ giving V = 79.0 V phase = 137 V line. [35%]

(c) The circuit diagram is drawn below. Fig. 3

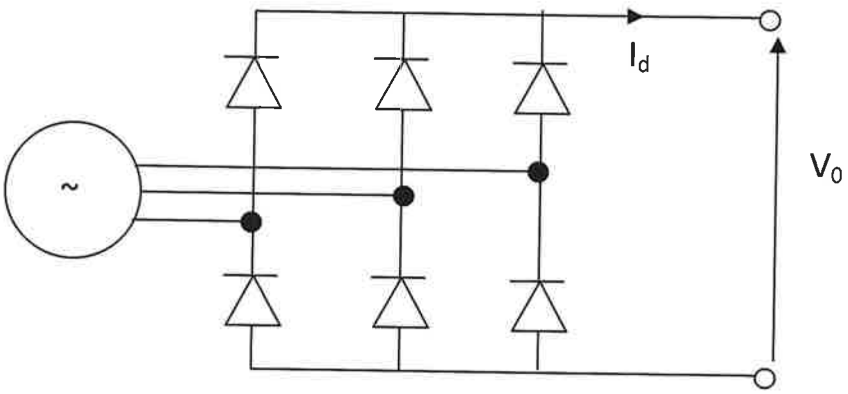

Fig. 3

The dc link voltage is given by $V_0 = 3\sqrt{2}V_L/\pi$ with V_L = 137 V giving 184.7 V. But this assumes ideal diodes. In reality, two diode forward voltage drops should be subtracted from this, giving 185 – 2.4 = 182.3 V.

Ignoring all losses, then $P=V_0I_d$, giving I_d=2960/182.3=16.2 A. [20%]

(d) Consider one of the generator phases, e.g. phase A. Its voltage is more positive than both phases B and C for 1/3 of a period, so, during this period, phase A supplies the DC link 'outward' flowing current. Similarly, for 1/3 of a period phase, A has the most negative voltage, so, during this period, phase A supplies the 'return' DC link current. Thus, the current in one phase will look as shown below. Fig. 4

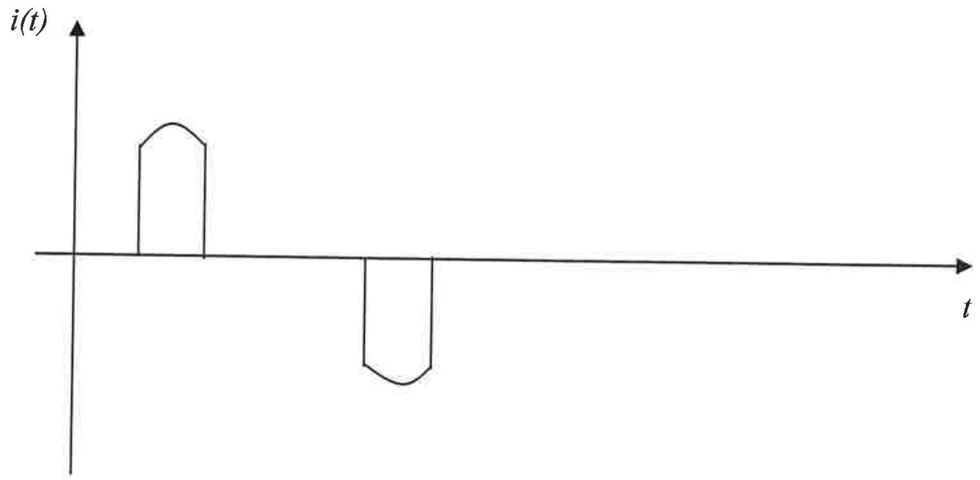

Fig. 4

Manufacturers give VA ratings for their machines based on certain assumptions, one of which is that the terminal voltage and resulting winding current will be sinusoidal. As the figure above shows, this is not the case for a PMG connected to a full-wave three-phase rectifier, and the current waveform consists of a fundamental component plus harmonics which will be at integer multiples of the fundamental frequency. Such harmonic currents cause additional power losses in the machine, so the PMG must be de-rated to account for this. Typically, a ball-park figure of 20% is used, so that if that rated output of the turbine is 10 kW, then a 12 kVA PMG might be chosen. [20%]

2. (a) Diversity of supply means connecting many different sources of renewable electricity into the grid. Increasing diversity creates an averaging effect, so for example, if it is windy in one part of the UK, but not in another, electricity can be supplied from wind turbines sites in the windier area to the less windy area. In turn, this enables the reliance on conventional generating plant to be reduced.

Two examples: Connecting of Danish wind power into the Nordic grid, which in turn has around 40 GW of hydroelectricity available.

DC link between France and the UK enables import/export of wind power. [15%]

(b) $I = (V_1e^{j\delta} - V_2)/jX$, so $I^* = (V_1e^{-j\delta} - V_2)/(-jX) = j((V_1e^{-j\delta} - V_2)/X$

$S_1 = 3V_1e^{j\delta}I^* = 3j(V_1^2 - V_1V_2e^{j\delta})/X = 3j(V_1^2 - V_1V_2(\cos\delta + j\sin\delta))/X$

$= (3V_1V_2\sin\delta)/X + j3(V_1^2 - V_1V_2\cos\delta)/X = P_1 + jQ_1$

$S_2 = 3V_2I^* = 3jV_2(V_1e^{-j\delta} - V_2)/X = 3j(V_1V_2(\cos\delta - j\sin\delta) - V_2^2)/X$

$= (3V_1V_2\sin\delta)/X + j3(V_1V_2\cos\delta - V_2^2)/X = P_2 + jQ_2$

These results show that $P_1 = P_2 = (3V_1V_2\sin\delta)/X$. Since the transmission line is assumed to be lossless, then it is expected that $P_1 = P_2$. Furthermore, assuming that V_1 and V_2 are roughly equivalent to 1 pu, then this shows that the flow of power is controlled by controlling the angle between the voltages at either end of the transmission line. Thus, to increase the power flow, δ must be increased. This corresponds to increasing the load angle of the synchronous generators, which in turn requires more torque to be provided at the generator shaft. If this torque is not supplied then the load angle does increase, but by the generator slowing down, and the grid frequency starts to fall. Thus, real power is controlled by monitoring the grid frequency and adjusting the load angles of the generators by supplying more input torque as required to bring the frequency back up to nominal.

The average value of Q1 and Q2 is the average reactive power flowing between the two ends of the line, and this is given by $3(V_1^2 - V_2^2)/2X$. This shows that the flow of reactive power is controlled by controlling the magnitudes of the voltages at the source and load ends of the transmission line. In practice these are controlled by the excitation voltage of the generators. [35%]

(c) First convert the 272 Ω reactance of the transmission line to per-unit.

$Z_b = V_b^2/VA_b = 275^2/500 = 151\ \Omega$ giving the pu reactance of 1.8. Adding in the pu reactances of T1 and T2, gives a total reactance of 2 pu. The maximum pu power that can be transmitted is $V_{1pu}V_{2pu}/X_{pu}$, corresponding to a 90 degree angle between V_1 and V_2. The maximum value for V_{1pu} is 1.2, and V_{2pu} is fixed at 1 pu. Thus $P_{maxpu} = 1.4\times1/2 = 0.7$, so $P_{max} = 0.7\times500$ giving 350 MW. This is below the maximum output power of the wind farm of 400 MW, so the existing grid infrastructure is inadequate. [20%]

(d) The principle of the upgrade is that the capacity of the main feeder connecting T1 and T2 will be increased by approximately $(400/275)^2$. In order to find the new capacity, first convert the 272 Ω main feeder reactance to per-unit.

$Z_b = V_b^2/VA_b = 400^2/500 = 320\ \Omega$ giving the pu reactance of 0.85. Adding in the pu reactances of T1 and T2 gives a total reactance of 1.05 pu, so a maximum capacity of $1.4\times1/1.05 = 1.14$ pu = 667 MW.

Now check that the system can handle the reactive power. There is no reactive power at the load end, but the process of transmitting the maximum power of 400 MW, which is 400/500 = 0.8 pu will require a current of 0.8 pu, so a reactive power to be generated of $0.8^2\times1.05 = 0.672$ pu.

Thus the average reactive power of $(Q_1+Q_2)/2$ will be $0.672/2 = 0.336$ pu $= (V_1^2 - V_2^2)/2X_{pu} = (V_1^2 - 1)/(2\times1.05)$.

Solving for V_1 gives 1.31 pu, which is below the maximum voltage of 1.4 pu.

Thus, the magnitude of the voltage at the wind farm is 1.31×11 kV = 14.4 kV.

The angle is found from $P_{pu} = V_{1pu}V_{2pu}\sin\delta/X_{pu}$ and so

$0.8 = 1.31\times1\times\sin\delta/1.05$ giving $\sin\delta = 0.641$ and $\delta = 39.9$ degrees. [30%]

3. (a) (i) The state of development.

Biomass: Power generator side is conventional steam plant except the boilers must be able to handle/burning biomass and, generally, handling biomass is an issue.

Barrages: Tidal turbines relatively mature. [10%]

(ii) The extent of resource.

Biomass: Resource can be useful but limited in nature e.g. chicken litter, waste chipboard, straw. Special crops (miscanthus) grass, willow and wood are, or can be, more widely available, but many complete with food crops.

Barrages: Limited number of suitable estuaries, but significant resource – e.g. Seven estuary could be ~10GW. [10%]

(iii) Major changes to estuarine conditions, impact on marine and bird life.

Biomass: Concern about large scale harvesting of timber, competition with food crops.

Barrages: Major changes to estuarine conditions, impact on marine and bird life. [10%]

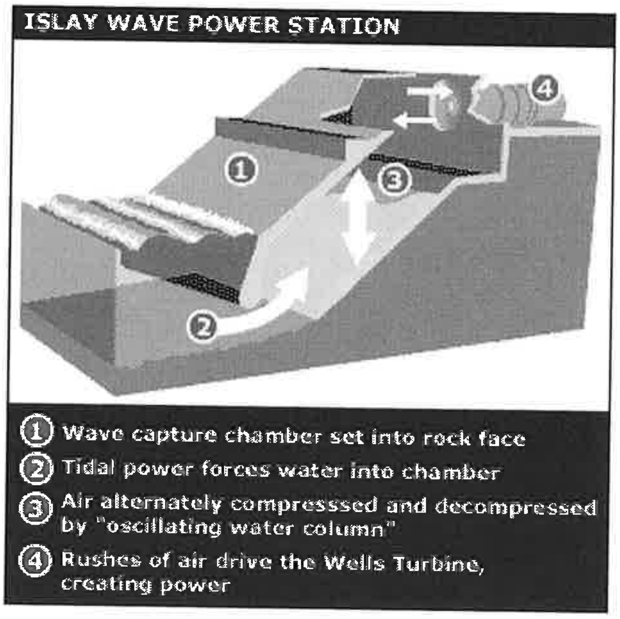

Fig. 5

(b) (i) An OWC device turns wave motion into air motion using a chamber, as in the 'Limpet' on Islay. The air is blown and sucked through a Wells turbine, a rectifying turbine which rotates in the same sense irrespective of the direction of air flow. "Hydraulic gearing" viz. a pipe of reducing diameter is used to get a greater air speed. An induction generator can be used (essentially fixed speed) although there are other options. [20%]

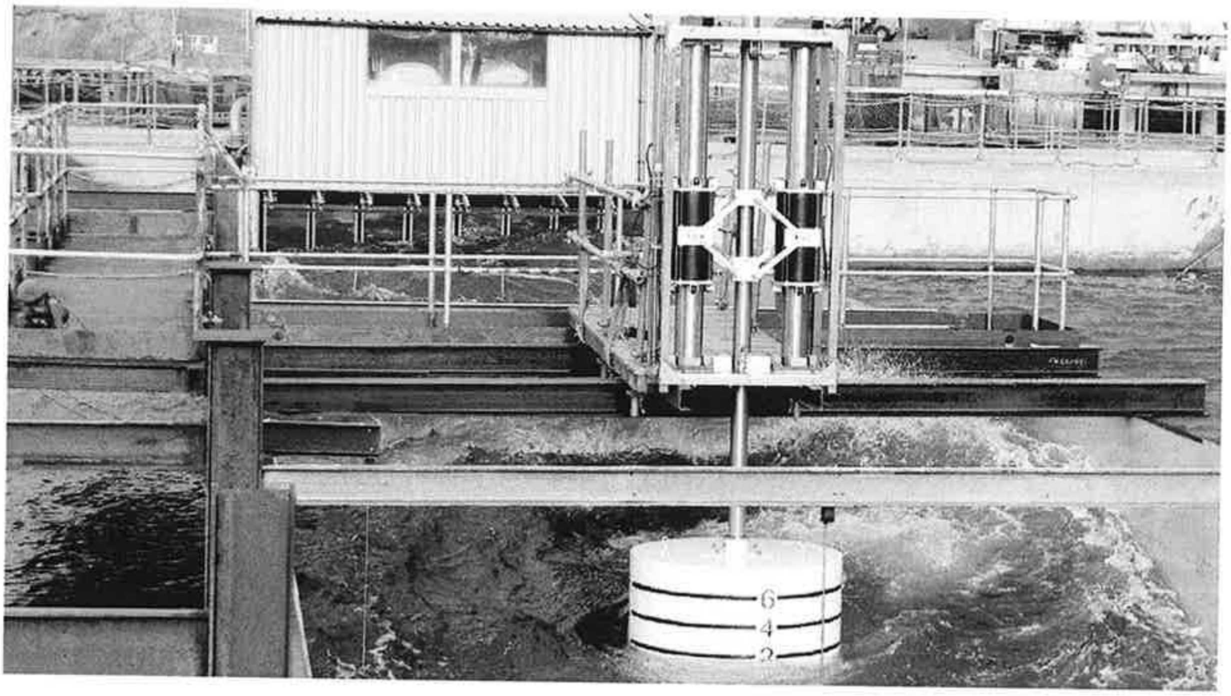

Fig. 6

(ii) The point absorber has a float which is small in size relative to the wavelength of the sea waves. The float moves up and down within the waves and this motion is used to drive a linear generator, for example a tubular air-cored machine. The output from a linear machine exhibits variable voltage and variable frequency, so an AC to AC converter is needed. AC to DC followed by inversion to fixed voltage, fixed frequency AC for supply to the grid. [20%]

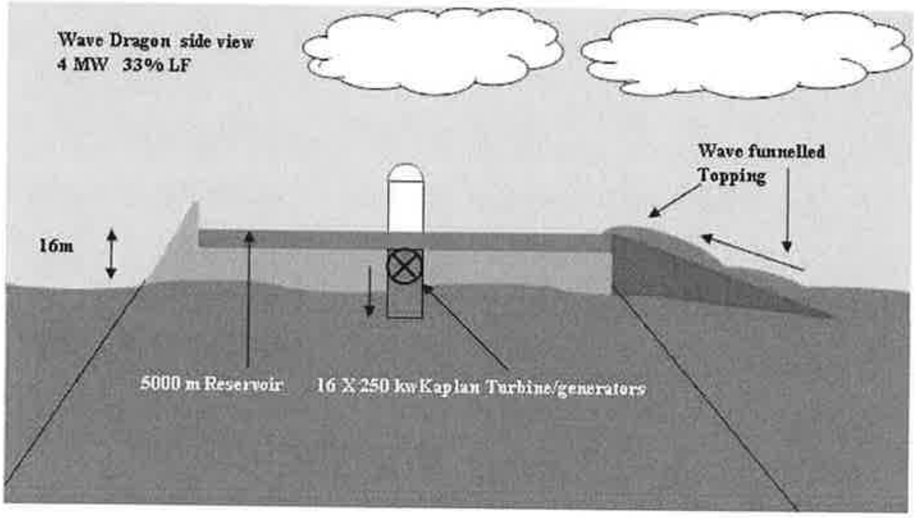

Fig. 7

(iii) The idea behind over topping devices is that wave crests overtop a reservoir and fill it with water. The water flows out via a turbine suitable for low head hydro-generation. This turbine can run at essentially fixed speed, so an induction generator is perhaps the natural choice, being essentially fixed speed, but with some "give", due to slip. [60%]

(c) Linking offshore wind farms, or maybe in the future wave farms, where the distances are too great for AC cables (say 40 nautical miles).

HVDC links are useful too for both power transfer and for balancing flows to even out variations in, say, wind farm output. Links can be between regions or international. The cable being laid in the Irish sea between Scotland and North Wales is an example. [10%]

4. (a) Benefits: higher capacity factor, fewer planning problems, easy access and maintenance.

Drawbacks: maintenance harder, environment tougher, harder to install, connection to grid more difficult. [10%]

(b)

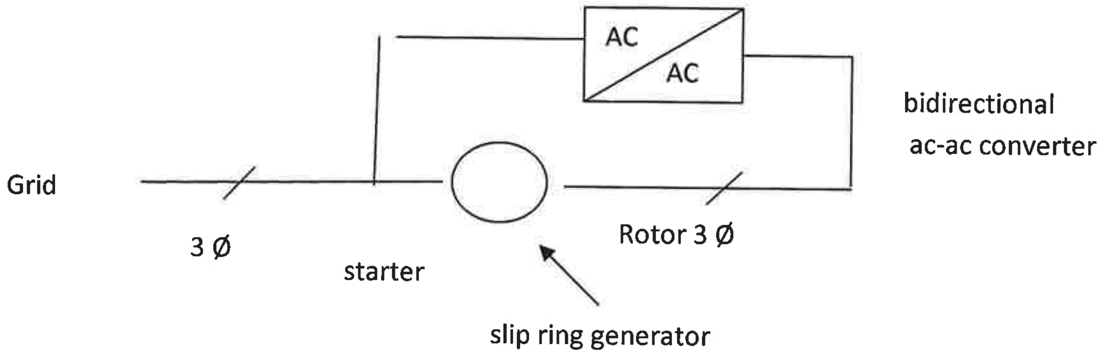

Fig. 8

Reasons for popularity: economy – only fractionally rated converter is needed. Also the slip ring induction generator is quite cheap relative to permanent magnet machines. [40%]

(c) (i) Natural speed is when control winding is supplied with DC (0Hz). Add baseline speed like the synchronous speed in ordinary induction machines.

$$N_n = \frac{50 + 0}{2 + 6} = 375\text{rpm}$$

(ii) Control winding output Pcw = power winding output Ppw $\left(\frac{N - N_n}{N_n}\right)$

So total output = $\left(1 + {}^{N}/_{N_n} - 1\right) P_{pw}$

Ppw = $\frac{3}{4}x6 = 4.5MW$

(c) (ii) Hence Pcw = $1.5MW$

(iii) PH 375 rpm $x\, {}^{4}/_{3}$

$$375x\frac{4}{3} = 500 = \left(\frac{50+f}{2+6}\right)60$$

So

$$f = \frac{500}{60}x8 - 50$$

$$= 66\,{}^{2}/_{3} - 50 = 16\,{}^{2}/_{3}\,Hz$$

(iv) The CW voltage is proportional to frequency, so will be maximum at $16\,{}^{2}/_{3}\,Hz$, assuming speed deviation downwards is no greater. A bidirectional converter will give nominally up to the same voltage as the grid, that is 690V. Allowing a margin would be sensible so use, say, 600V at $16\,{}^{2}/_{3}\,Hz$.

(v) To go to 1 ½.Nn means going up to 25Hz on the control winding and to stay within converter rating would need to be rewound for say 25Hz@600V, i.e. fewer turns. [50%]

30/5/2013

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4B19 Renewable Electrical Power Short answers 2013

1 . (b) (i) Diameter = 5.85 m (ii) Output power = 2.96 kW, angular speed = 24.6 $rads^{-1}$, input torque = 120 Nm, phase current = 12.5 A, line-line output voltage = 137 V (c) DC link voltage = 182.3 V, DC link current = 16.2 A

2. (c) Maximum power = 350 MW (d) Voltage at wind farm = 14.4 kV at an angle of 39.9^0.

4. (c) (ii) Power winding output = 4.5 MW, control winding output = 1.5 MW (iii) Frequency = 16.7 Hz (iv) Voltage rating around 600 V.