Module 4B19 2017 Crib

1 (a)

One of the main problems of renewable electrical energy sources is that the power outputs from renewable sources often vary widely and sometimes unpredictably, especially in the case of wind power. Peak output may not match well to times of peak demand. To help overcome this problem excess energy can be stored when supply exceeds demand, which can be recovered when demand exceeds supply.

Pumped storage schemes; batteries (chemical energy); compressed air energy storage; heat storage; flywheel storage, hydrogen.

(b) (i) FAVOURABLE LOCATION & SIGNIFICANT RESOURCE
Countries that have significant lengths of coastline are obviously best placed to exploit wave generation and the UK is particularly fortunate in this respect: the economically recoverable resource for the UK has been estimated to be around 90 TWh/year or about 25% of the country's annual consumption of electricity.

POWER OUTPUT PREDICTABILITY
The power output from such renewable sources is relatively predictable. Tides, for example, are a result of the relative motion of the earth and moon and are fairly regular (although the height of tides is seasonal and can vary according to location).

(b) (ii)HOSTILE MARINE ENVIRONMENT
One significant challenge is the construction of reliable systems in a hostile marine environment. Wave and tidal systems must survive in the sea and withstand a 'one-in-50-year' wave, as well as a constant battering. Generally the best sites have the roughest weather.

POWER TRANSMISSION & POWER SYSTEM CAPABILITY
Transmitting the power to shore is another challenge. The best sites tend to be far from the main load centres and must be transmitted over long distances, which incurs losses. The present UK grid is not capable of handling significant renewable power flows and requires costly upgrades.

REGULATORY BARRIERS, SUBSIDIES & ECONOMICS
Marine energy schemes and the consequential power transmission works face substantial regulatory barriers, requiring statutory consents from a number of Government departments before development can take place. The Crown Estate is landowner of the UK seabed and areas of foreshore and its permission is required for the placement of structures or cables on the seabed.

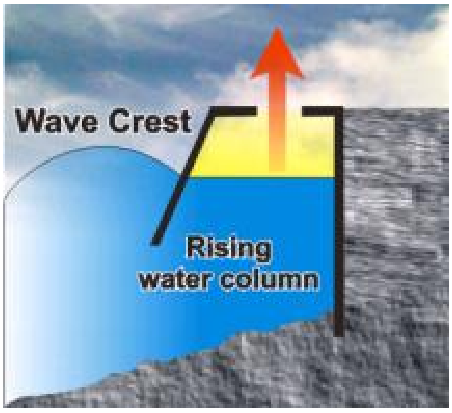
Marine energy schemes also face strong opposition from interest groups, despite the industry's green credentials. Developers, and the subsidies they receive, are subject to changes in Government policy. Renewable energy currently enjoys a subsidised pricing regime, but that can change. Ultimately, marine energy schemes must compete with conventional generation schemes, and this is dependent on future carbon politics and the availability and price of fossil fuels.

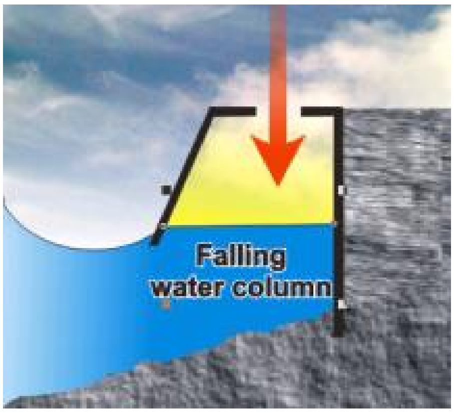
RELATIVELY IMMATURE FIELD WITH NO PREFERRED SOLUTION
The field is immature, and, unlike with wind generation, there is no obvious preferred solution apart from marine current turbines (however, there is much ongoing research supported both publicly and privately).

ENVIRONMENTAL DAMAGE & SHIPPING DISRUPTION

There is a risk of affecting the local marine environment: disrupting the habitats of marine life, pollution from chemicals if used, e.g., hydraulic oil. Careful planning needs to occur to avoid disrupting existing shipping lanes, e.g., commercial and private vessels.

(c) (i) Oscillating water column





Near-shore or shoreline system. Incoming rising wave pushes air into a chamber and the falling wave removes the air. This air flows through a Wells turbine (a bi-directional device), which drives a generator. OWCs can use pneumatic gearing to achieve high force/velocity at the turbine, allowing a smaller and cheaper turbine. Wells turbines rotate in the same sense irrespective of the direction of the airflow, but its efficiency is generally low (around 40%).

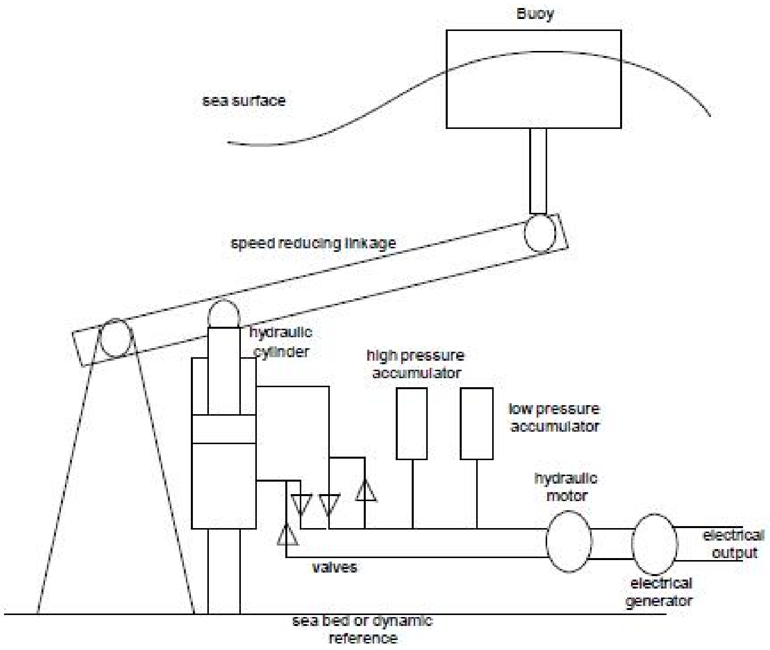
The Wells turbine is usually coupled with an induction generator and inertia of combined system can provide some smoothing of power flow. Cage rotor induction generator will have limited range of speed and will absorb VARs, so need an electronic power converter. DFIG with fractionally-rated converter another option, which can also generate VARs. A PM machine is also possible, but needs full-rated converter.

(c) (ii) Buoy-type systems

Point absorber: a floating structure that converts buoyant motion relative to the base into electrical power. Point absorbers move with the incident wave and are relatively small compared to wavelength. Generally near-shore or deep-water.

The power take-off method could be via a hydraulic system (see figure), where hydraulic motors can be used to drive as high-speed, cage induction machine, which are connected directly to the grid. Hydraulic accumulators can be used to smooth power flow. However, hydraulic motors are not particularly efficient, especially for partial loads; reliability issues and possibility of hydraulic fluid leakage.

Another option is direct drive with a linear PM machine (e.g., vernier hybrid or air-cored linear machines), which is simpler mechanically, but the output from such machines is incompatible with the grid, so power conversion is necessary.



Assessor's comments

Very popular question, attempted by many candidates and generally very well answered. Some candidates confused explanations of wave power devices and a reasonable number forgot to explicitly describe the power take-off (type of generator and converter, if required).

2(a) (i)The BDFM has two electromagnetic couplings from the stator to the rotor, one of which replicates the effect of the rotor-connected, fractionally-rated converter in the DFIG.

The stator has two windings (power and control windings) of differing pole numbers. The pole-pair numbers must differ by at least 2 to avoid unbalanced magnetic pull, e.g., 2/6, 4/8 pole, and different pole numbers implies no electromagnetic coupling of stator windings.

The rotor has a nested loop construction designed to couple both stator-driven fields, such that the frequency and distribution of the rotor currents induced by the first air-gap field (power winding) matches that induced by the second air-gap field (control winding).

Thus, the stator windings are coupled to the rotor windings, even though their pole numbers and frequencies are different. Power winding connected directly to 50 Hz, three-phase grid; control winding connected to grid via bi-directional, fractionally-rated converter (power winding = stator winding in DFIG, control winding = rotor connection in DFIG).

(ii)

1. Gets rid of brush gear and associated maintenance/reliability problems
2. Still enables a fractionally-rated converter to be used
3. Cage-type rotor can be used: more reliable and less expensive
4. Controllable operation at an exact or 'synchronous' speed
5. Adjustable power factor, like the DFIG
6. Operation as a mains-fed ('conventional') induction machine if the converter fails

(b) A reasonable range of variable speed operation is required in tidal current turbines, which suggests the use of a doubly fed induction generator (or BDFM). A fractionally-rated converter is required for the double feed, which usually needs to be bi-directional. A full-rated converter allows flexibility such that conventional synchronous or induction generators could be used.

It is also possible to connect directly to the grid without the use of a converter, but this has significant disadvantages, e.g., a hydraulic system could be used to drive a high-speed, cage induction machine. However, there are issues regarding efficiency, reliability and the possibility of hydraulic fluid leakage. A conventional, direct drive PM machine could also be used, but this requires a low speed machine of large diameter; to avoid impeding flow, special machines like rim machines need to be used.

(c) (i)
Natural speed of a BDFM is the speed when the control winding is fed with DC, so $f_2 = 0$.
$N_n = 60f_p/(p_p+p_c) = 60*50/(2 + 4) = 500$ rpm
Speed range of ±20%: 400 – 600 rpm

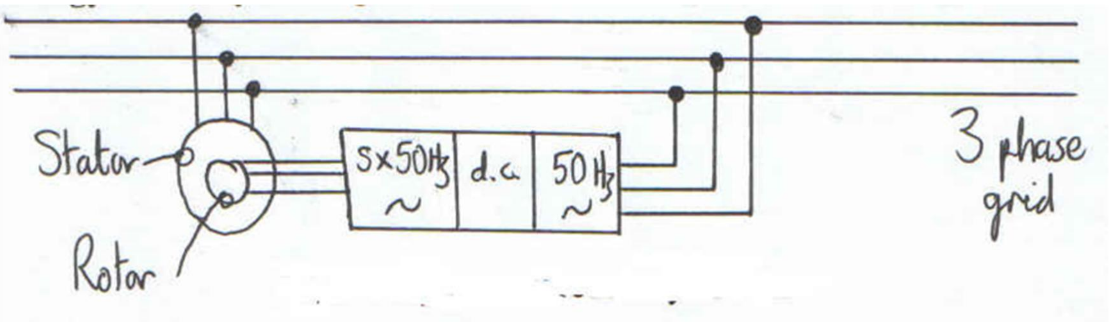
(c) (ii)
The maximum power is at 60 kW (at 600 rpm). Control winding power related to deviation from natural speed and the fractional speed deviation is 100/500 = 1/5.
Power output = $P_{\text{power winding}} + P_{\text{control winding}}$, so 60 kW = $P_p + P_p/5$. P_p = 50 kW
Since 0.8 lagging power factor for both windings: VA_p = 62.5 kVA, VA_c = 12 kVA

(d) Maximum output when modulation index, m, is 1. $690 = \sqrt{3}\, V_{DC} / 2\sqrt{2} \rightarrow V_{DC} = 1127$ V
This is, of course, a minimum value. Give some **safety margin** to account for variations in grid-side voltages: around 1200-1300 V would be reasonable, but higher voltages would require higher rated components, which would be more expensive.

Peak device (e.g., IGBT) voltage in inverter = dc link voltage = 1127 V (or 1200-1300 V if using value with safety margin).
On the output side of the converter, assuming max. power output is 60 kW (neglecting converter losses for simplicity), the current can be calculated:
$P = \sqrt{3}*V*I*\cos\Phi$, so $I = 60000/(\sqrt{3}*690*0.8) = 62.76\ A_{rms}$
Hence, peak current $I_{peak} = \sqrt{2}*62.76 = 88.75$ A
Rating of inverter = 1127*88.75 ≈ 100 kVA

Assessor's comments
Attempted by roughly half of the candidates. Many could not adequately explain BDFM construction/operation. Calculations generally fine, but part d) very poor, especially VA rating. Many candidates calculated dc link voltage, but didn't account for any safety margin.

3 (a) The 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 of the output power. The PEC can be operated such that the DFIG can generate reactive power.



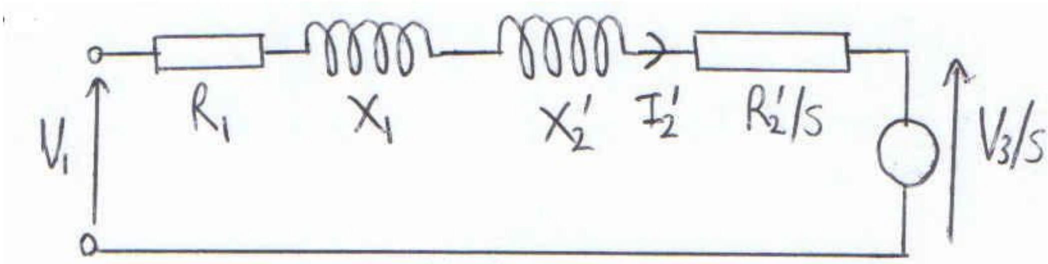
The PEC enables 3-phase voltages to be fed in to the rotor slip rings at a variety of magnitudes, frequencies and phases. In particular, by adjusting the frequency, the rotor speed may be varied since doing this directly controls the DFIG slip. Hence, the torque-speed characteristic of the DFIG can be 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. This is exactly what is required to enable variable speed control.

(b) (i) Using $P = \frac{1}{2} C_p \rho A v^3$ and putting in $C_p = 0.4$, $\rho = 1.23$ kgm^{-3}, $A = \pi R^2$ with R = 40 m and v = 10 ms^{-1} gives $P_{rated} = 1.24$ MW

(ii) The most probable wind speed is 6 ms^{-1}, at which the injected rotor voltage is zero, and so the DFIG synchronous speed at 50 Hz must correspond to the optimum turbine angular speed at this wind speed. Since the optimum tip-speed ratio is 0.8, and using $\lambda = \frac{\omega R}{v}$ give $\omega = 1.2$ rads^{-1} at the turbine, and so with a gearbox of ratio 30, at the generator $\omega = 36$ rads^{-1}. Equating this with $\omega_s = 2\pi f/p$ in which p is the number of pole-pairs and f = 50 Hz gives p = 9 i.e. 18 pole generator.

(iii) The generator angular speed at the 6 ms^{-1} wind speed will be approximately synchronous speed which is $2\pi f/p$ with f = 50 Hz and p = 9 giving 34.9 rads^{-1}. The rated wind speed is 10 ms^{-1} and so the generator speed will increase to $34.9 \times 10/6 = 58.2$ rads^{-1} and so the slip is $(34.9-58.2)/34.9 = -2/3$. The generator torque is given by $T\omega = -1.24$ MW so T = -21.3 kNm.

(iv) Referring to the equivalent circuit below:



$P_{in(elec)} = 3I_2'^2(R_1+R_2'/s) + 3V_3'I_2'/s$

$P_{loss} = 3I_2'^2(R_1+R_2')$ and $P_{conv} = 3V_3'I_2'$ assuming that the converter is controlled such that it only generates/absorbs real power.

$P_{in(elec)} - P_{loss} - P_{conv} = P_{out(mech)}$ and so

$T\omega_r = T\omega_s(1-s) = 3(I_2'^2R_2'(1-s) + V_3'I_2'(1-s))/s$

giving $T = 3(I_2'^2R_2' + V_3'I_2')/s\omega_s$

(v) To estimate V₃' we assume that the torque-speed curve is steep around the no-load speed, and so the no-load slip is approximately -2/3:

$s_{nl} = -2/3 = V_3'/V_1$ and so $V_3' = -0.667 \times 11000/\sqrt{3} = -4234$ V (phase)

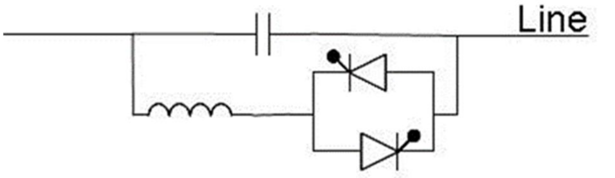
Equating the torque of -21.3 kNm with the rest of the torque equation with $V_3' = -4234$ V and s = -2/3 gives I =38.9 A., Further iterations based on improved estimate for V_3' make no difference.

Assessor's comments

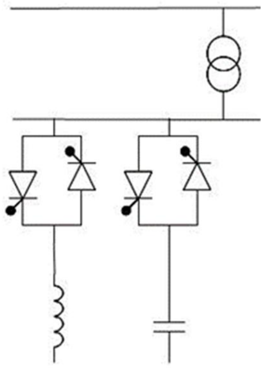
Most students did well at the bookwork of (a) and the more straightforward calculations of (b) parts (i), (ii) and (iii). The DFIG torque proof was less well attempted, and very few candidates were able to determine the DFIG current in part (v).

4. (a) An example of increasing diversity of supply is the HVDC link across the Channel that links the French and British grids together. What this means is that if there are high winds in the UK and hence high wind farm power output then the excess power can, if necessary, be exported to France. Conversely, if wind in the UK are low but not in France, then excess wind power can be exported from France to the UK. Thus, diversity of supply is the idea that by having greater grid interconnection means that more renewable sources can be integrated into the grid because doing so will smooth out the unpredictable nature of many renewable sources of electricity, in the same way that it does for electrical loads.

(b) FACTS are defined by the IEEE as "a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability."



An example series-connected FACTS system is shown above. This enables the feeder impedance to be controlled by placing capacitance in series with the naturally inductive line, thereby cancelling out some of the line reactance, which in turn means that the line can transmit more power for a given load angle (or for the same power can operate at a more conservative load angle).



A shunt-connected FACTS system is shown above, this enables reactive power to be absorbed or generated at the load bus, to compensate for that consumed by the load. This is key to enabling voltage control of the grid within acceptable limits.

(c) Choose VA_b to be 200 MVA and base voltages of 11 kV, 275 kV and 33 kV. Since the transmission network is purely inductive, all of the wind farm power will reach the load i.e. 100 MW and so the pu load P will be 0.5. Both transformers have ratings equal to VA_b and so no change of base is required for these. However, the feeder impedance needs to be converted to a pu value. Z_b at the feeder is given by $Z_b=V_b^2/VA_b$ with V_b = 275 kV giving 378 Ω and so $Z_{pu}=50/378$ = 0.132.

Thus the total pu impedance between wind farm and load bus is 0.132+0.15+0.2=0.482

(i)0.6 lagging means the load pu Q is $P\tan\varphi = 0.5\tan(\cos^{-1}0.6) = 0.667$ and pu $S = 0.5/0.6 = 0.833$

Since the pu voltage at the 33 kV bus is 1 pu the $I_{pu} = 0.833$

At the wind farm end, the pu power is 0.5 pu but the pu Q will be $Q_{load}+I^2X_{pu} = 0.667+0.833^2\times0.482 = 1.00$ pu.

$S_{pu} = \sqrt{(0.5^2 + 1.00^2)} = 1.12$ pu and so since $V_{pu}I_{pu} = S_{pu}$ $V_{pu} = 1.12/0.833 = 1.34$ and so the voltage will be 1.34×11 kV = 14.8 kV. Angle of E wrt I is $\tan^{-1}(Q/P)$ giving 63.4^0. Angle of load bus voltage wrt I is $\tan^{-1}(Q_{load}/P_{load}) = 53.1^0$ and so the angle of E wrt to load bus voltage is 10.3^0.

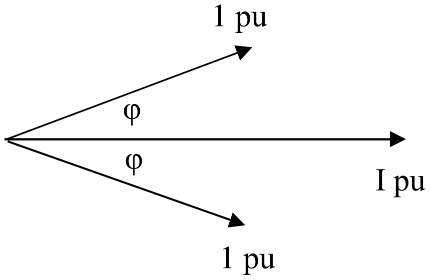
For 0.8 leading $Q = -0.375$ pu, $S_{pu} = 0.5/0.8 = 0.625$ and so I_{pu} is also 0.625.

At the wind farm end, the pu power is 0.5 pu but the pu Q will be $Q_{load}+I^2X_{pu} = -0.375+0.625^2\times0.482 = -0.187$ giving $S_{pu} = 0.534 = V_{pu}\times0.625$ giving $V_{pu} = 0.854$ and so the voltage will be 0.854×11 kV = 9.40 kV. Angle of E wrt I is $\tan^{-1}(-0.187/0.5)$ giving -20.5^0. Angle of load bus voltage wrt I is $\tan^{-1}(Q_{load}/P_{load}) = -38.7^0$ and so the angle of E wrt to load bus voltage is 18.2^0.

This is a large range for the excitation voltage of the generator, and that could cause problems for other feeders connected to the wind farm bus.

(ii) When wind speeds are lower the output power of the wind farm is also lower, thus the load bus P and Q will be reduced. This will mean that a lower load angle is required to transmit the power, and the voltage at the wind farm will also be reduced because less Q is being transferred.

(d) Since the power at both ends of the line are the same, the angle between the voltage at the source and the current must be the same as that between the voltage at the load and the current (always true). But, if the voltage at both ends is also constrained to be 1 pu, then the only possibility is shown in the phasor diagram below.



$P_{pu}=V_{pu}I_{pu}\cos\varphi = I_{pu}\cos\varphi$

Also $I_{pu}X_{pu}=2\sin\varphi$

Eliminating I_{pu} results in $\sin2\varphi=X_{pu}P_{pu} = 0.482\times0.5$ giving $\varphi = 7.0^0$ and then solving for I_{pu} gives 0.506

This means that the total required load pu $Q = 1\times0.506\times\sin(-7^0) = -0.0616$

For the lagging load Q = 0.667 and so the FACTS system has to generate 0.667+0.0616 = 0.729 pu = 146 MVAr. Thus capacitors are required that can generate 146 MVAr at 33 kV.

For the leading load Q = -0.375 whereas we require -0.0616 and so the FACTS system has to absorb 0.313 pu = 62.7 MVAr. Thus inductors are required which can absorb 62.7 MVAr at 33 kV.

Assessor's comments

Parts (a) and (b) are bookwork and in general were very well answered. Many excellent answers to the calculation of part (c), but only one candidate managed to answer part (d) concerning operating a flat grid using FACTS devices.

Tim Flack

Mark Ainslie

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