EE4-48

The Answer

1.

a) Why are the steam turbine generators two-pole machines?

[3]

Ans:

Steam turbine offers much better efficiency at high speed and also better damping. Also higher speed means lower diameter machine – smaller size, so the overall cost.

b) Why are furnace and boiler dynamics not represented in electromechanical stability study?

[2]

The time scale of electromechanical stability problem is less than 10-20 seconds. The time constants associated with steam production in boiler and heat production process in furnace are in the range of minutes. In view of this the furnace and boiler dynamics can be treated very slow process.

c)

i) Why is the transfer function of a hydro-turbine non-minimum phase type?

[4]

The power output of a hydro turbine is proportional to the pressure of the water. With additional opening of the gate – the pressure of the water heating turbine blade drops – initially dropping the power output. The power output gradually catches up with added gate opening. This process can be modelled in transfer function domain as a right half plane zero. So the transfer function is a non-minimum phase type.

ii) How is such turbine dynamics controlled in practice?

[3]

The students are expected to mention about the difficulty of controlling non-minimum phase system because of reduced phase margin – they are expected to suggest gain reduction during transients (high frequency) through governor etc..

d)

i) Synchronous generators have large synchronous reactance (usually greater than 2.0 p.u.) - Explain the reason(s).

[3]

Synchronous generator has large number of windings and also small air gap between the stator and rotor. This results in low reluctance path for the magnetic circuit in the steady state resulting in large synchronous reactance.

ii) Why, despite having such a large reactance, the fault current fed by a synchronous machine is large (about 4.0 p.u)?

[5]

During the fault, the path of the flux produced by the stator MMF is largely through air as the field wind opposes sudden changes in flux linking itself. This result in high reluctance temporarily, so the reactance is small. Low reactance, known as transient and subtransient) results in large current.

e) Two synchronous generators (Gen A and Gen B) of similar capacity are made by two manufactures. The clearance (air gap) between the stator and rotor of Gen A is 1.25 times that of Gen B. Both generators are loaded equally. Following a temporary disturbance the rotors of the generators started swinging. Which generator will offer higher margin of stability and why?

[5]

The stability margin in power is the difference between the power being produced and the maximum that can be produced. The maximum power that can be produced is inversely proportional to synchronous reactance. Gen A has larger airgap , so the reactance will be 1/1.25 times that of Gen B –all other condition remaining the same. The maximum power that can be produced by Gen A is 1.25 times higher – so Gen A will offer higher margin of stability. The peak of the power angle curve for Gen A being higher to produce the same power , the load angle of Gen A will be less- so Gen A will have higher stability margin in power angle terms as well.

[Total = 25 marks]

2. a) A 3-phase, star connected, 20 kV (line); 600 MVA alternator is connected to the grid operating at 50 Hz. The resistance is negligible and synchronous reactance is 1.25 Ohm.

i) Find out the excitation voltage (line-line) (magnitude and angle) when the generator is delivering full load at 0.85 power factor lagging.

[6]

MVA $= 600$

$V_L = 20\ kV$

$X_s = 1.25\ \Omega$

Pf $= 0.85$ *lag*

phase angle $= -\cos^{-1}(0.85) = -31.78^0 = \varphi$

$$
\begin{aligned}
E_{fd} &= V_t + j\sqrt{3}\bar{I}_L X_s \\
&= V_t + j\sqrt{3}\frac{MVA}{\sqrt{3}V_t} X_s \angle\varphi \\
&= V_t + j\frac{MVA}{V_t} X_s \angle\varphi \\
&= 20 + j\frac{600}{20} \times 1.25\angle -31.78 \\
&= 51\angle 39 \\
delta &\approx 39^\circ
\end{aligned}
$$

ii) The excitation voltage is now increased by 20% keeping the prime mover power fixed. How will the power output (both MW and MVAR) be affected by way of this change?

[6]

$$P = \frac{E_{fd}V_t}{X_s}\sin\delta$$

Since the prime mover power is not changing, the load angle will change to keep the output power at fixed P

Say new load angle is δ_{new}

$$
\begin{aligned}
P &= \frac{1.20E_{fd}V_t}{X_s}\sin\delta_{new} \\
P &= \frac{E_{fd}V_t}{X_s}\sin\delta \\
1.20\sin\delta_{new} &= \sin\delta \\
\sin\delta_{new} &= \frac{1}{1.2}\sin\delta = \frac{1}{1.2}\sin 39^\circ \\
\delta_{new} &= 31.4^\circ
\end{aligned}
$$

Reactive power in both cases

Normal excitation $= \frac{E_{fd}V_t}{X_s}\cos\delta - \frac{V_t^2}{X_s}$

$= \frac{51 \times 20}{1.25}\cos 39 - \frac{20^2}{1.25} = 314\ MVAr$

Increased excitation of 20% $= 1.2 \times \frac{51 \times 20}{1.25}\cos 31.4 - \frac{20^2}{1.25} = 516\ MVAr$

iii) Keeping the excitation voltage at the value obtained in (i), if the prime mover power is gradually increased the generator will continue to deliver increased MW before steady state stability limit is reached; Compute the stability limit (in terms of MW). [5]

Stability margin

$$\frac{E_{fd}V_t}{X_s} - \frac{E_{fd}V_t}{X_s}\sin\delta$$

$$\frac{51 \times 20}{1.20}[1 - \sin 39°] = 302\ MW$$

b) A synchronous generator produces a terminal voltage of 9 kV (phase). This is connected to a network which has many other machines. The power flow solution obtains a 15 degree phase angle (θ) with respect to some reference angle. The load angle delta (δ) is 25 degree with respect to the same reference angle. The output current is 10 kA and 0.85 pf lagging with respect to the terminal voltage. Find the following quantities.

i) direct and quadrature axis voltages in the machine reference frame [4]

ii) direct and quadrature axis currents in the machine reference frame [4]

Assume d axis is leading q axis (IEEE convention)

$V_{mach} = \bar{V}_{network}e^{-j\delta}$

$I_{mach} = \bar{I}_{network}e^{-j\delta}$

0.85 pf lagging with respect to terminal voltage

$\bar{V}_{network} = V_{network}\angle 15°$

$\bar{I}_{network} = I_{network}\angle 15° - 31.78°$

$= I_{network}\angle -16.78°$

Current is given here with respect to terminal voltage vector- so, the angle of current into network reference is shifted by the voltage angle $\theta + \varphi$

$V_{mach} = 9\angle 15°\, e^{-j25} = 9e^{j(-25+15)} = 9e^{-j10}$

$= 8.86\text{-}j1.56\ kV$

I_{mach} = $10\angle - 16.78° \, e^{-j25}$
$10e^{-j41.78} = 7.457 - j6.662 \, kA$

[Total = 25 marks]

3.

a) The terminal voltage of a synchronous generator is suddenly dropped by 20% because of a temporary remote fault in the network. This resulted in temporary drop in power produced by the generator. The input mechanical power remained at the pre-fault value. This resulted in a dynamic response of the generator which is characterised very approximately by the following equations:

$$\frac{d\delta}{dt} = \omega_r - \omega_s \quad (3.1)$$

$$\frac{d\omega_r}{dt} = \frac{\omega_s}{2H}\left[P_{mech} - \frac{E'V_t}{X_d'} sin\delta - D(\omega_r - \omega_s)\right] (3.2)$$

δ: load angle, ω_r : rotor speed, ω_s: synchronous speed (314 rad/sec), P_{mech} : mechanical input power, E' transient speed voltage , V_t : terminal voltage, X_d': direct axis transient reactance, H: H constant, D: damping coefficient (pu/rad).

i) What are the roles of P_{mech} and E' in influencing the dynamics characterised by the above two equations?

[5]

In this model, the roles of P_{mech} and E' are inputs. The dynamics driving them are ignored to have a classical electromechanical model. Both these inputs can be controlled to improve the stability of the system. Fast valving is precisely implements this through mechanical power input. The excitation voltage will be influenced by automatic voltage regulator (AVR)- the effect is improved transient stability margin by increased synchronising torque. Both the inputs (mainly E') can be controlled to improve the oscillatory behaviour of the system.

ii) Treating P_{mech} and E' as inputs develop the lineralised state space equations in the form:

$$\dot{x} = Ax + Bu$$

$$x = [\Delta\delta, \Delta\omega_r], u = [\Delta P_{mech}, \Delta E']$$

[7]

$$\frac{d\delta}{dt} = \omega_r - \omega_s$$

$$\frac{d\omega_r}{dt} = \frac{\omega_s}{2H}\left[P_{mech} - \frac{E'V_t}{X_d'} sin\delta - D(\omega_r - \omega_s)\right]$$

$$\frac{d\Delta\delta}{dt} = \Delta\omega_r$$

$$\frac{d\Delta\omega_r}{dt} = \frac{\omega_s}{2H}\left[\Delta P_{mech} - \frac{E_0'V_{t_0}}{X_d'}\cos\delta_0.\Delta\delta - \frac{V_{t_0}}{X_d'}\sin\delta_0.\Delta E' - D\Delta\omega_r\right]$$

$$\frac{d\Delta\delta}{dt} = \Delta\omega_r$$

$$\frac{d\Delta\omega_r}{dt} = -\frac{E_0'V_{t_0}}{X_d'}\cos\delta_0.\frac{\omega_s}{2H}.\Delta\delta - \frac{\omega_s}{2H}D\Delta\omega_r + \frac{\omega_s}{2H}\Delta P_{mech} - \frac{\omega_s}{2H}.\frac{V_{t_0}\sin\delta_0}{X_d'}\Delta E'$$

$X_1 = \Delta\delta,\quad X_2 = \Delta\omega_r,\quad u_1 = \Delta P_{mech},\quad u_2 = \Delta E'$

$$\dot{X} = AX + Bu$$

$A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \quad B = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix}$

$a_{11} = 0;\ a_{12} = -1.0;\ a_{21} = -\frac{E_0'V_{t_0}}{X_d'}\cos\delta_0\frac{\omega_s}{2H};\quad a_{22} = -\frac{D\omega_s}{2H}$

$b_{11} = 0;\quad b_{12} = 0;\quad b_{21} = \frac{\omega_s}{2H};\quad b_{22} = -\frac{\omega_s}{2H}.\frac{V_{t_0}\sin\delta_0}{X_d'}$

iii) Obtain the element of matrix A, B for the following values of the parameters and operating variables:

δ= 40 degree, ωs= 314 rad/sec), P_{mech} =1.0;: E'= 1.5 p.u. Vt =1.05 p.u.

Xd'= 0.3 p.u. H= 6.0 s, D=0.04 (pu/rad)

[5]

A = [0 1.0000
-37.8960 -0.3768];
B= [0 0
9.4200 -21.1838]

iv) Obtain the eigenvalues of the system matrix

[4]

Eigenvalue =

-0.1884 + 6.1531i
-0.1884 - 6.1531i

v) Frequency of oscillations (imaginary part of the eigenvalue pair in Hz)

[2]

0.9793 Hz

vi) Comment on the stability of the system.

[2]

The system eigenvalue has negative real part, so it is stable.

[Total = 25 marks]

4.

a) What is the performance co-efficient (C_p) in a wind turbine ?

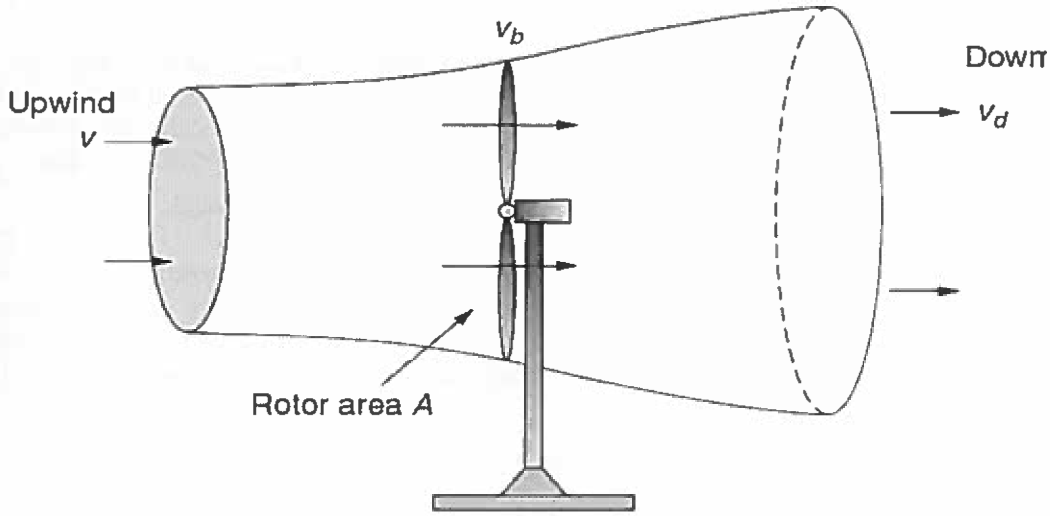
[2]

The performance co-efficient is the conversion factor in wind energy production. For a particular wind turbine design it is the fraction of the incoming kinetic energy of the wind that is converted to mechanical through rotation of turbine blade. It is function of incoming wind speed and the speed of the wind immediately after leaving the turbine blade.

b) Show that the theoretical maximum value of C_p is 16/27 or 59.3 %.

[8]

Look at the figure below



Assume the rotor swept area is A, the upwind speed is v, the downwind speed is v_d, the average wind speed at blades is $v_b = \frac{v+v_d}{2}$, and the mass flow of air is $\dot{m}$
The power extracted by the blade is

$$P_b = \frac{1}{2}\dot{m}(v^2 - v_d^2)$$

the mass flow of air can be expressed as

$$\dot{m} = \rho A v_b$$

Substituting $\dot{m}$ into P_b yields

$$P_b = \frac{1}{2}\rho A\left(\frac{v+v_d}{2}\right)(v^2 - v_d^2)$$

Assume $\lambda = \frac{v_d}{v}$, the expression of P_b becomes

$$P_b = \frac{1}{2}\rho A\left(\frac{v+\lambda v}{2}\right)(v^2 - \lambda^2 v^2)$$

$$P_b = \frac{1}{2}\rho A v^3\left[\frac{1}{2}(1+\lambda)(1-\lambda^2)\right]$$

$$P_b = \frac{1}{2}\rho A v^3 C_p$$

with C_p is equal to turbine efficiency.

In order to find the maximum value, take the derivative of C_p with respect to λ and set this to zero

$$\frac{dC_p}{d\lambda} = \frac{1}{2}[(1+\lambda)(-2\lambda) + (1-\lambda^2)] = 0$$

After simple calculation, the solution is $\lambda = \frac{1}{3}$. Substituting back the value of λ into C_p results

$$C_p = \frac{1}{2}\left(1+\frac{1}{3}\right)\left(1-\frac{1}{3^2}\right) = \frac{16}{27}$$

c) This part relates to gear box in a wind turbine generator (WTG)

i) What is the function of the gear box in a WTG?

[2]

Generally wind turbine rotate at 4-6 RPM depending on the wind speed/radius of the blade. This is way too low to generate electrical power at power frequency such as 50 and or 60 Hz. The shaft to which the generator is connected rotates at high speed. The high shaft speed is produced by the gear box – having lesser teeth on the generator shaft and larger teeth on the turbine side shaft.

ii) Why is the gear box optional in Type-4 (Full converter machine)?

[3]

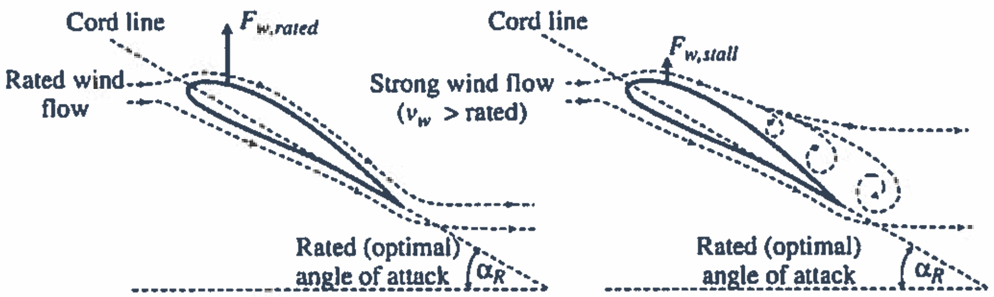
In full converter the power frequency is produced from DC output voltage which is rectified from stator AC voltage – so the frequency of stator output voltage does not govern the output frequency of a full converter machine. That way gear box is not required as any frequency that stator produces is rectified to DC. This eliminates the gear box , thus more reliable and machine with less maintenance requirement

d) This part relates to stall control in WTG

i) What is meant by stall control in wind energy conversion system?

[3]

Stall control alters the lift force that is produced because of the differential pressure on the top surface and bottom surface. Generally it reduces the lift force by making the flow of the wind on the top surface of the blade.



(a) At rated wind speed (b) Above rated wind speed

(ii) Why is stall control not effective below the rated wind speed?

[3]

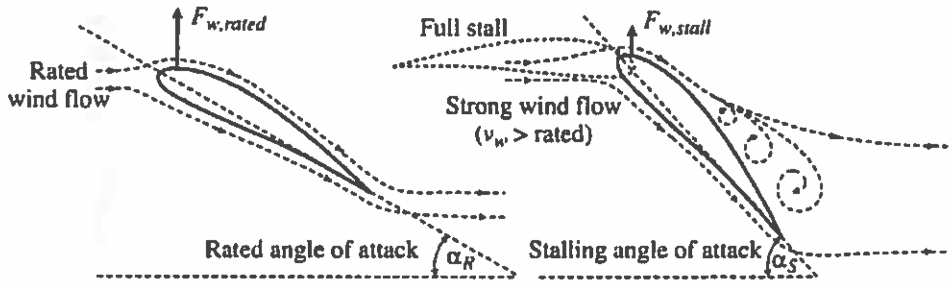
Since through stall control lift force is reduced – the net mechanical torque (and so power) produced is also reduced. Below rated wind speed it is not desirable to have this as the output power produced is reduced further.

(iii) How does active stall control differ from passive stall control ?

[4]

In passive-stall control, the angle of attack is designed to work optimally at the rated wind speed. If the wind speed increases above the rated speed, the laminar wind flow above the cord is disrupted, causing the turbulence. As a result, the lift force is reduced with the rotational speed. Passive-stall technique is an effective measure to avoid the turbine from mechanical failure.

In addition to the higher wind speed, the stall can also be caused by increasing angle of attack. It then reduces the power captured from the incoming wind. It can be carried out by rotating the blade around its axis using hydraulic system so that the blade facing more into the wind. Using this mechanism, the turbine power can be maintained at rated value. The basic principle and the turbine power curve of this control scheme are shown in the figure below.



(a) At rated wind speed (b) Above rated wind speed

[total = 25 marks]