The Answer

1.

a)

i) How is the switching surge in power networks characterised? [2]

It is an over voltage, voltage is expressed in kilo volts (RMS) over time. Time is generally expressed in micro seconds. The students are expected to show the voltage versus time.

ii) How does the switching surge influence circuit breaker design and operation? [2]

Excessive over voltage results in stress in insulation of major components. It is very important to have an estimate about the over voltage for insulation design and coordination. This will guide the circuit insulation and voltage stress handling capability

b)

i) What is oscillatory instability in the context of power system operation? [5]

I like the students to attempt along the following lines

Following a severe imbalance between power input and electrical power output, generator rotor either accelerate or decelerate – usually this is known as transient stability – the associated control action recover the situation – [2 marks]

But before reaching a final equilibrium – system passes through some oscillations – these results from the action of the control of the transient stability.

Since power system is a huge electromechanical mass – the balance of the energy exchanges between mechanical and electrical form of storage – which manifest as oscillations, mainly in the low frequency range – but can include higher range of frequency also. Usually proliferation of control of phenomenon at different time scales have been seen to be contributing to the situation – as an example a high gain, fast acting voltage regulator improves transient stability but worsens small signal or oscillatory stability. Damping is usually inadequate - [3 marks]

ii) Why such instability is of diminishing concern in the context of renewable generation? [3]

I expect the student to mention that large synchronous generations are now being replaced by more decentralised power electronics interfaced generation – this decouples the dynamics between the generation to the network – so oscillatory instability involving mechanical mass is now of less concern – but stability though – there can be pure instability in the network involving electrical energy storing elements only.

iii) A system is transiently stable but it can be oscillatory unstable- justify this statement [2]

During transient stability maintaining of synchronisation is very important – after that is done – the system is allowed to settle in an equilibrium- the post disturbance dynamics are normally of slower time scale giving rise to action from other types of controls. Overall damping of the system will be contributed by the response of those relatively slower control and in many cases the damping turns out to be inadequate.

iv) How is such instability in the system prevented? [3]

Normally supplementary control loops with limits – knows as power system stabiliser or damping control through various voltage and power flow control devices – I expect the student to write few sentences about power system stabiliser, its structure and function. Anyone mentioning about FACTS controller will be highly appreciated.

c)

i) What is the primary purpose of having a speed governing system? [2]

Student should talk about primary frequency control, droop, and its impact on maintaining a stable frequency – this is done through speed governing system.

ii) Why is it relatively difficult to design speed governing system for hydro turbine for operating a large synchronous generator? [3]

I am expecting the student should argue through the transient negative gate opening and power output relationship.. then they should connect this with a right half plane zero – and its additional phase lag – leaving little margin etc.. should take the help of the block diagram , transfer functions etc.

iii) What is transient gain reduction in the context of speed govern control design? [3]

Transient gain reduction is a mechanism which produces lower gain or reduced response at high frequency input. For a sudden change in gate input – power output drops .. at that situation best is not to sense that drop in power further increase in gate opening – so a high frequency transient gain reduction block can be added to filter out high frequency disturbances- at relatively low frequency – the gain is less.

[25 marks]

2.

a)

i) How does amortisseur winding help in system stabilisation? [3]

Any deviation in rotor speed from the airgap stator magnetic field will result in voltage induced in rotor body and physical winding. The rotor being a closed circuit equivalent winding or amortissuer bar having closed path allows current to flow which produces a counter torque to oppose the cause of the deviation between air gap MMF and rotor body – so when rotor accelerates – the counter torque oppose the acceleration and vice versa – the rotor speed is stabilised around synchronous speed.

iii) How is an amortisseur winding modelled in power system stability study? [3]

I am expecting them to write flux dynamics with impressed voltage to be zero. They should say it is a short circuit – the model is through transient and subtransient flux or equivalent voltage in q-axis and subtransient in d-axis

iii) A round rotor synchronous generator has synchronous reactance of 2.2 pu on its own base. When sudden short circuit happens at rated terminal voltage – the initial current is 4-5 times the rated current which lasts for about 4-6 seconds followed by a gradual fall. Why is the generator initial output current so high? [4]

The student should be able to write what happens magnetically when a sudden short circuit appear, path of the stator flux – and how they vary with time [2 marks]

Once they can establish that initially the reactance is sub-transient in nature which is very small (say about 0.25 p.u) –this will produce the undesirably high currents – with the passage of time – the flux tend to flow more through rotor body so stator self and mutual inductances will increase limiting the current. [2 marks]

iv) Why does not synchronous generator permit identical overload capability both in the lagging as well as leading power factor range? [4]

The flux reinforcement during the leading power factor based synchronous generation saturates the end ring and increases the eddy current ... [2 marks]

This leads to the losses and heating in the end winding region – thus the permitted output is less than that as lagging power operation. [2 marks]

v) What is the purpose of d-q transformation in synchronous machine modelling and analysis? [3]

I am expecting students to write about the difficulty to deal with time variation in inductance- so they need to move to find a method – the current, voltage all become along two axis and are DC during normal operation. They should choose carefully the axis etc . Then they should state dealing with dc current is easier, inductance becomes function of time and rotor angle.

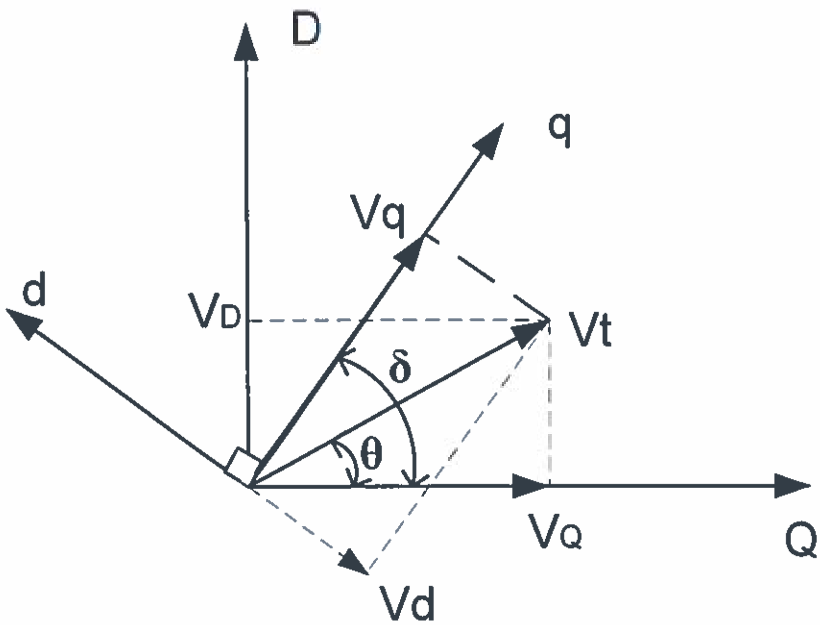
vi) Despite having a d-q transformation, why is it necessary to have machine to network reference frame transformation? [3]

Each machine is modelled in its own dq (Park) co-ordinate taking the terminal voltage as reference– the load angle of each machine is different from the other machine – so with respect to the network or Kron reference frame each individual machine has to be represented again requiring machine (Park) to Network (Kron) transformation.

vii) Express the relationship between machine to network frame assuming the angle difference between the two reference frames is δ-θ. [5]

[25 marks]

Let us assume that the network reference frame is expressed as DQ and that of machine as dq. If V is a voltage of a bus with an angle θ with respect to DQ reference; its corresponding component in machine reference frame would be a rotation of (δ-θ).



[2]

Synchronous reference frame with respect to network reference fram

$VQ + j\,VD = Vt\,e^{j\theta}$

$$VQ = Vt \cos \theta$$
$$VD = Vt \sin \theta$$

Resolving VQ and VD along machine reference d-q will produce

$$Vq = VQ \cos \delta + VD \sin \delta$$
$$Vd = -VQ \sin \delta + VD \cos \delta$$
$$Vq + j\, Vd = Vt\, e^{-j(\delta-\theta)}$$

[3]

3.

a)

Fig Q3.1 shows a simple power system model with one synchronous generator connected to a power network through generator transformer and a section of power transmission line to deliver real and reactive power to the system. The values of various parameters shown in the diagram are as follows.

E = 3.0 pu, V_t = 1.0 p.u, X_s= 2.0 p.u, X_t=0.1 p.u, X_l= 0.2 p.u , δ = 30 degree

i) Compute the real and reactive power at the network end [5]

$$X = X_s + X_t + X_L = 2.0 + 0.1 + 0.2 = 2.3\,pu$$

Complex power received at the network end: $V_t I^*$

$$I = \frac{E\angle\delta - V_t\angle 0}{jX} \Rightarrow I^* = \frac{E\angle -\delta - V_t\angle 0}{-jX} = \frac{E\angle -\delta - V_t\angle 0}{X}\angle \pi/2 = \frac{E\angle(\pi/2-\delta) - V_t\angle \pi/2}{X}$$

$$S = P + jQ = V_t\angle 0 \frac{E\angle(\pi/2-\delta) - V_t\angle \pi/2}{X} = \frac{EV_t}{X}\sin\delta + j\left[\frac{EV_t\cos\delta - V_t^2}{X}\right]$$

[3marks]

$$P = \frac{EV_t}{X}\sin\delta = \frac{3\times 1}{2.3}\sin 30 = \frac{1.5}{2.3} \approx 0.65\,pu$$

$$Q = \frac{EV_t\cos\delta - V_t^2}{X} = \frac{3\times 1\times\cos 30 - 1^2}{2.3} = \frac{1.6}{2.3} \approx 0.7\,pu$$

[2marks]

b)

Because of a transient disturbance in the system, the network voltage dropped slightly and temporarily initiating the electromechanical dynamics of the generator connected to the system. Assuming a classical swing equation model (speed ω_r and load angle δ as only dynamic variables) with an inertia constant H (sec) and damping constant D (in pu)

i) Write down the swing equations [4]

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

$$\frac{d\omega}{dt} = \frac{\omega_s}{2H}\left[\left(P_m - \frac{EV_t}{X_s + X_t + X_l}\sin\delta - \frac{D}{\omega_s}(\omega - \omega_s)\right)\right]$$

In state space form,

$$\begin{bmatrix}\Delta\dot{\delta}\\ \Delta\dot{\omega}\end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{\omega_s}{2H}\frac{E_0V_t}{X_s + X_L + X_t}\cos\delta_0 & -\frac{D}{2H}\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta\omega\end{bmatrix} + \begin{bmatrix}0\\ \frac{\omega_s}{2H}\end{bmatrix}[\Delta P_m]$$

[4 marks]

ii) For the following values of the operational variables and constants, obtain the linearized dynamics in state space form treating mechanical power as input and generator real power as output.

$E = 3.0$, $V_t = 1.0$, $X_s = 2.0$, $X_t = 0.1$, $X_l = 0.2$, all in pu $\delta = 30$ degree, $H = 5.0$ sec, $D = 10.0$ p.u, operating frequency is 50 Hz or 314 rad/sec. [8]

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

$$\frac{d\Delta\omega}{dt} = \frac{\omega_s}{2H}\left[\left(\Delta P_m - \frac{E_0V_t}{X_s + X_L + X_t}\cos\delta_0\Delta\delta - \frac{D}{\omega_s}\Delta\omega\right)\right]$$

[3 marks]

In state space form.

$$\begin{bmatrix}\Delta\dot{\delta}\\ \Delta\dot{\omega}\end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{\omega_s}{2H}\frac{E_0V_t}{X_s + X_L + X_t}\cos\delta_0 & -\frac{D}{2H}\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta\omega\end{bmatrix} + \begin{bmatrix}0\\ \frac{\omega_s}{2H}\end{bmatrix}[\Delta P_m]$$

[3 marks]

Obtain the numerical values of the state matrix
Astate = [0,1;-35.48,-1.0]

[2 marks]

iii) Comment on the small signal stability of the system with the help of obtained eigen-values of the system state matrix [8]

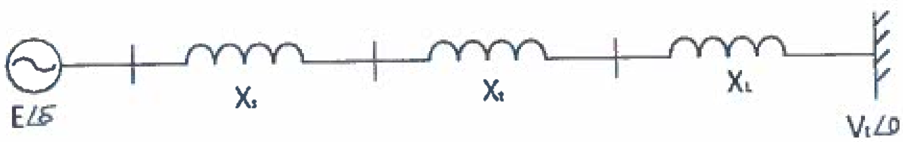


Fig Q3.1 A Simple Power System

[25 marks]

Eigen value of this state matrix = -0.5+j5.9345; -0.5-j5.9345. I computed this from Matlab , they will be required to solve the second order characteristic equation so will be challenged both intellectually as well as time wise.

[6 marks]

The system has complex conjugate poles – so it is oscillatory in nature. since the real part or the poles are in the left half of eigen-plane. it is oscillatory stable

[2 marks]

4.

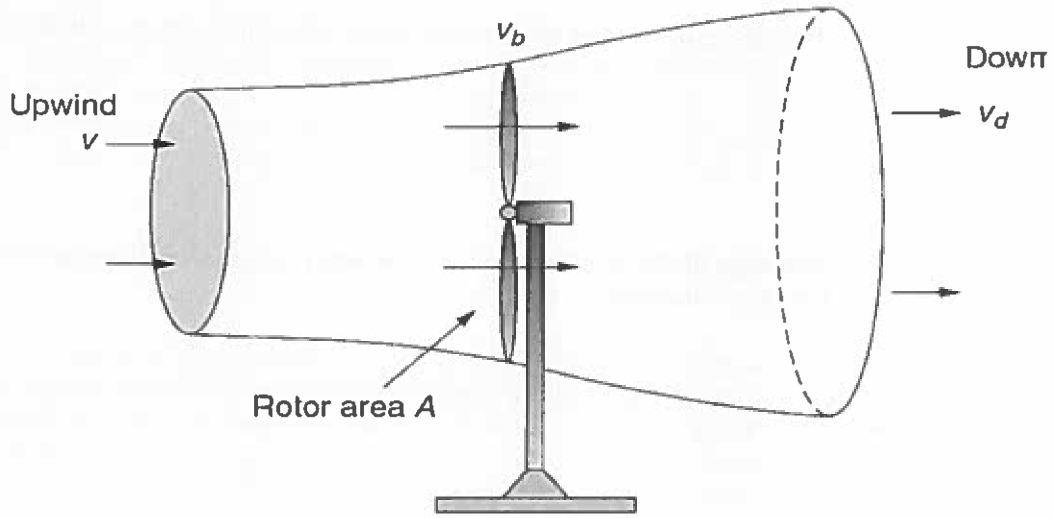
a)

i) What is the performance co-efficient (C_p) of 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.

ii) Show that the theoretical maximum value of C_p is 16/27 or 59.3 %. [7]

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 $\dot{m}$

[1 marks]

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

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

[2 marks]

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.*

[2 marks]

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*

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

[2 marks]

iii) What is the function of the gear box in a wind turbine generator (WTG)? [2]

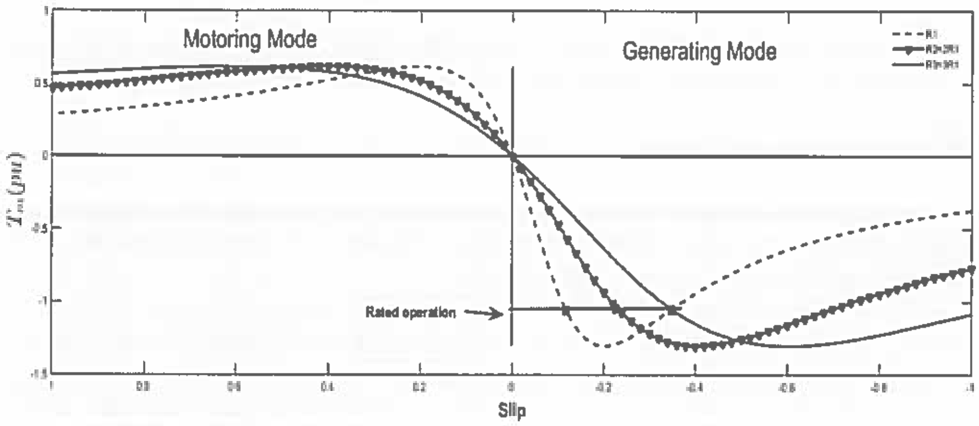
Generally wind turbine rotate at 4-6 RPM depending on the wind speed/radius of the blade. This is way too low to generate electrical power at power frequency such as 50 and or 60 Hz. The shaft to which the generator is connected rotates at high speed. The high shaft speed is produced by the gear box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

iv) Why does the Type-4 (full converter machine) machine have large number of poles in the rotor? [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 but because generator rotor now spins at around 10 rpm , one needs large number of poles to produce a power output at higher electrical frequency .

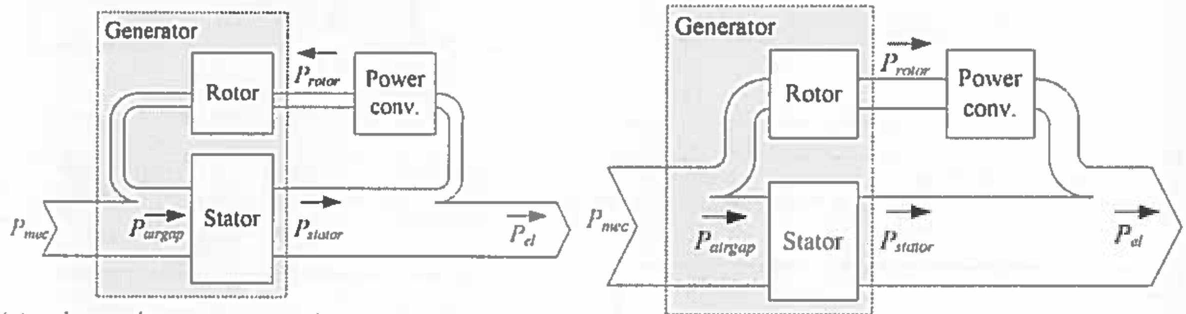
v) How does the insertion of an external resistance in the rotor circuit help capture more energy from the variable wind? [3]

The steady-state analysis of wound rotor induction generator will vary as the rotor resistance varies. This is shown in the figure below. It can be seen that as the rotor resistance increases, induction generator can operate at a higher slip to produce the same rated output. This is useful when the speed of incoming wind changes.



vi) How is it possible to operate a Type-3 (DFIG) machine at lower than synchronous speed (positive slip) in generator mode? [3]

DFIG can operate both in sub-synchronous and super-synchronous region. Sub-synchronous region is when the rotor speed is below the synchronous speed. Whereas, the super-synchronous region when the rotor speed is higher than the synchronous speed. During these conditions, the power flow in the back-to-back converter is different as illustrated in the figure below [5]



(a) sub-synchronous operation

(b) super-synchronous operation

DFIG operation mode

In sub-synchronous region, the value of the slip is positive. Therefore, the power must be injected into the rotor in order for the generator to produce the power. Note, during this condition, the previous types of wind turbine cannot generate the electric power. During the super-synchronous region, the power from the mechanical input is divided into power flowing from the stator and rotor. The rotor power is a significant fraction from the stator power.

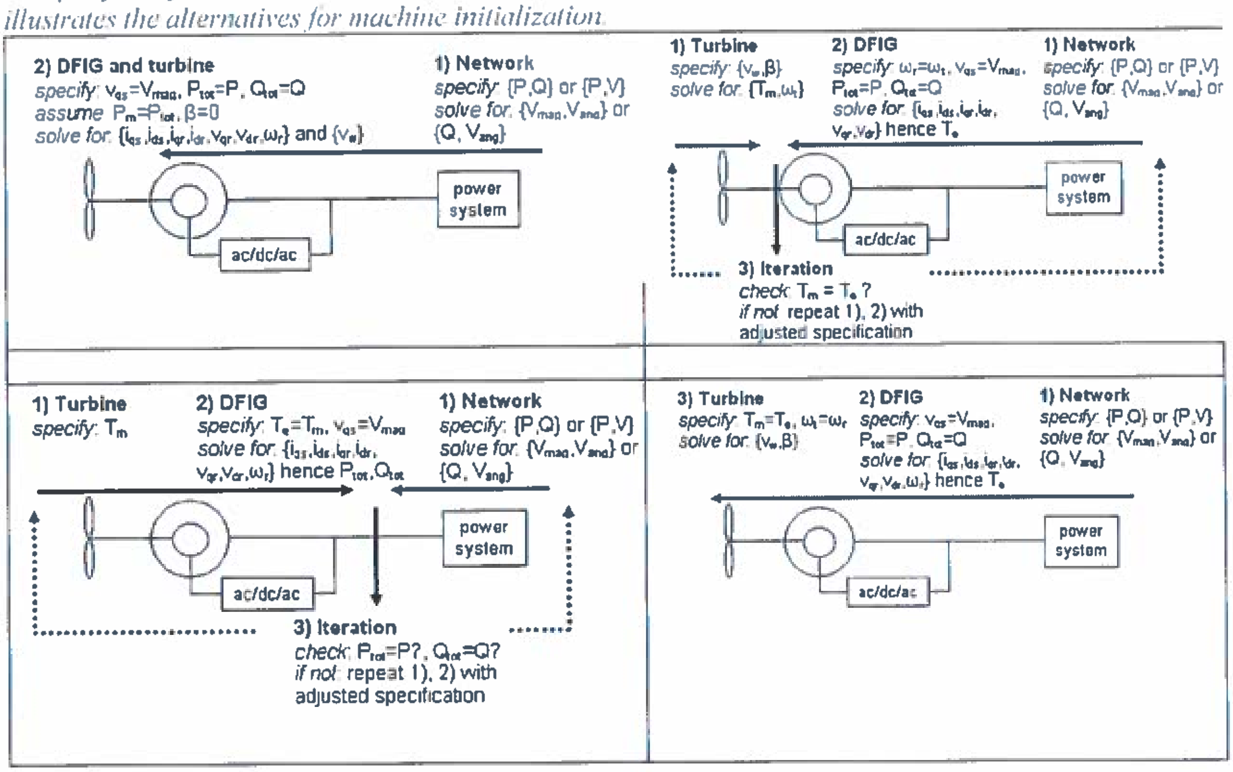
vii) Describe the approach of obtaining the initial values of voltages, currents, angles, speed to start a dynamic simulation when prevailing wind speed is less than the rated one? [5]

I am not expecting the student to solve the initial conditions rather assessing their understanding of how to set the solution to obtain them – I like them to touch on what are the different unknown and fixed variables, what are the interface variable etc. Because it is a subrated condition pitch angle should be zero, power flow should be taken as input to obtain stator voltage and angle, assumptions on no losses has to be made etc… Electrical torque as function of stator and rotor current and again as function of rotor speed have to be related

Outstandingly detailed answer can be as follows

Different from synchronous machine initialisation, in induction machine the rotor speed is unknown in subrated regime. In addition to that, the rotor voltage equations add up into the algebraic equation constraint. This allows different initialization procedure proposed.

It is proposed a method for initialization in subrated regime only with angle β equal to zero. It is also assumed that the machine is lossless ($P_m = P_{tot}$). The generator is therefore initialised from the output side (electrical) to the input side (wind speed). In other approaches the generator is initialized from the output and the turbine is from the input (wind speed). The method performs an iterative procedure until the variables in the interface between the generator and the turbine match. The choosen interface is between T_e and T_m. In some cases the interface is selected at the generator output so that $P_{tot} = P$ and $Q_{tot} = Q$. The iterative procedure is required due to the fact that the generator output and turbine input are specified. If the turbine input is left unspecified, the method is non-iterative. The figure below illustrates the alternatives for machine initialization.



The details procedure are given by

- Step 1: Using the load flow, the solution of V_{mag},V_{ang}, P_{tot} and Q_{tot} at generator bus is obtained.
- Step 2: There are two conditions:
    - ✓ **Subrated condition:** Using loadflow solutions and setting $v_{qs} = V_{mag}, v_{ds} = 0, P_{tot} = P_s + P_r, Q_{tot} = Q_s$ and $T_e = T_{e,ref} = K_{opt}\omega_r^2$ solve for rotor voltage and current and speed. This is a system of 7 equations with 7 unknown variables ($i_s^q, i_s^d, i_r^q, i_r^d, v_r^q, v_r^d$ and ω_r)
- Step 3:

- ✓ **Subtrated condition:** SpecifyT_m=T_e and $\omega_t = \omega_r$.. Solve $P_m = 0.5\rho\pi R^2 C_{pmax} v_w^3$ for v_w with $P_m = T_m\omega_t$and$\beta = 0^0$.

[25 marks]