Tutorial 7

Q1

a) ϕ=36:37° → cos ϕ = 0:8; sin ϕ = 0:
   P_o = S cos ϕ = 10 * 0.8 = 8 kW

b) The phase voltage is V_{ph} = 208/√3 = 120 V

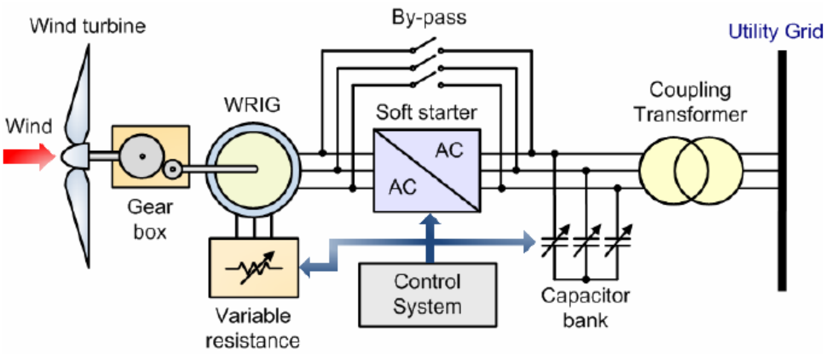
I = P/3 V_{ph} cosϕ = 8000 / 3 * 120 * 0.8 = 27.78 A

c) Q = S sinϕ = 10 * 6 = 6 kVAR

d) $P_{o1} = 8000 = 0.5A\rho V_{w1}^{3} c_{P1} * \eta$
   $P_{o2} = X = 0.5A\rho V_{w2}^{3} c_{P2} * \eta$
   $P_{o1}/P_{o2} = V_{w1}^{3} c_{P1} / V_{w2}^{3} c_{P2}$
   $P_{o2} = P_{o1} * V_{w2}^{3} c_{P2} / V_{w1}^{3} c_{P1} = 8000 * 8^{3} * 0.8 * c_{P1} / (12^{3} * c_{p1}) = 1896.3$ W

Q2

a)



Gearbox: Used for speed transmission from slow rotor hub speed to high generator speed.

WRIG: Used to convert mechanical power to electrical power at the grid voltage and frequency within a certain rotor speed range.

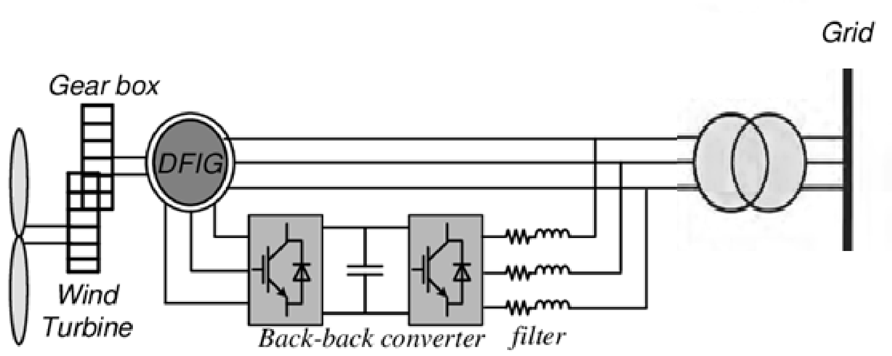
Soft starter: is a power electronics converter used to reduce the inrush current and transient torques during connection or disconnection of the generator to the grid.

Capacitor bank: capacitor bank is normally connected to improve the power factor at the connection point (reduce reactive power consumption by the induction generator)

Optically controlled variable resistors: used to allow a limited variable speed range of about 10% above synchronous speed.

Control system: Controls the soft starter operation, bypass switches, capacitor bank, and the variable resistors.

Coupling Transformer: steps up the voltage from generation level typically at 690V to collection network voltage level (typically 33kV) b)



Gearbox: Used for speed transmission from slow rotor hub speed to high generator speed.

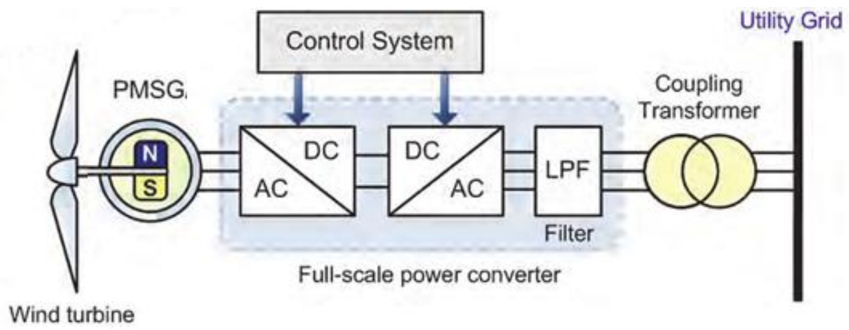
WRIG: Used to convert mechanical power to electrical power at the grid voltage and frequency within a certain rotor speed range. The stator windings directly connected to the constant-frequency three-phase grid, rotor circuit connected to back-to-back power converters

Back-to-back power converters: A rotor side converter is used to operate the DFIG at unity power factor and along the maximum power point tracking curve (optimal tip speed ratio) within ±30% slip. A grid side converter is used to exchange slip power with the grid at unity power factor while maintaining constant dc link voltage. Both converters are rated to 30% of WRIG/WT power rating.

Filter/choke: smoothing inductors are connected between GSC and the grid to filter out harmonics. A transformer may be used instead of the choke if rotor circuit voltage is designed to be higher than stator circuit voltage to reduce currents and losses in power converters.

Control system: Controls the RSC and the GSC switching.

Coupling Transformer: steps up the voltage from generation level typically at 690V to collection network voltage level (typically 33kV) c)



PMSG: Used to convert mechanical power to electrical power without the use of gearbox. Typically the rotor hosts large number of permanent magnet poles to allow operation at low speed. The stator windings directly connected to the constant-frequency three-phase grid, rotor circuit connected to back-to-back power converters

Back-to-back power converters: A Machine side converter is used to control the PMSG and ensure operation on the maximum power point tracking curve (optimal tip speed ratio) within the operating speed range. A grid side converter is used to exchange WT power with the grid at unity power factor while maintaining constant dc link voltage.

Filter/choke: smoothing inductors are connected between GSC and the grid to filter out harmonics.

Control system: Controls the RSC and the GSC switching.

Coupling Transformer: steps up the voltage from generation level to collection network voltage level (typically 33kV)

Q3

a)

Synchronous speed

$n_s = 120\, f/p =$ 120*50/4 = 1500 rpm

Generator speed at pitch activation n_r = 121/100*1500 = 1815 rpm

Gear ratio = generator speed/ blade speed = 1815/20 ≈ 91 (i.e. gear ratio 1:91)

b) slip when pitch is activated = $(n_s-n_r)/n_s$ = (1500-1815)/1500 = – 0.21

Rotor frequency = s*grid frequency = 0.21*50 = 10.5 Hz

(Notice that we discard minus sign as negative frequency has no physical meaning)

c) It is clear from Figure Q3 that at the speed 1.21pu where pitch mechanism is activated, the WT/generator produces 0.75pu power.

At pitching, generator speed in rad/s $\omega_{r\_g} = 2\pi n_r/60$ = 6.28*1815/60 = 189.97 rad/s

$T_e = P_e/\ \omega_{r\_g} = 0.75*2.3*10^6\ /\ 189.97$ = 9.084 kN.m.

The value of the torque at the rotor hub is subject to the gear ratio.

T_{e_hub} = 91*9080.4 = 826.315 kN.m.

d) It can be seen from Figure Q3 that at wind speed 11 m/s, the turbine operates at the maximum power point tracking curve (MPPT) corresponding to optimal tip speed ratio. Rotor blade speed at 11m/s wind speed is 1.1 pu.

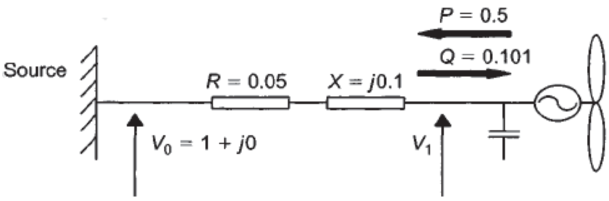
At the generator: ω_{r_g} = 1.1 *2π *ns/60 = 172.7 rad/s

At the rotor hub: ω_r = 172.7/91 = 1.898 rad/s

Optimal tip speed ratio $\lambda = \omega_r*R/V_w$ = 1.898 * (110/2) / 11 = 9.49

Q4

Applying KVL



$V_1 = V_o + I\,(R+jX) = V_o + (R+jX)x(S^*/V_1^*)$ Note: $S = 0.5-j0.101$pu or $S= V_1I^*$
so $I = S^*/V_1^*$

$$V_1^{(n+1)} = 1 + (0.05 + j0.1)(0.5 + j0.101)/V_1^{*(n)}$$

For the 1st iteration ($n = 0$) assume $V_1^{*(0)} = 1 + j0$; then $V_1^{(1)}$ may be calculated to be

$$V_1^{(1)} = 1.0149 + j0.0551$$

For the 2nd iteration ($n = 1$)

$$V_1^{*(1)} = 1.0149 - j0.0551$$

then

$$V_1^{(2)} = 1.0117 + j0.0549$$

For the 3rd iteration ($n = 2$)

$$V_1^{*(2)} = 1.0117 - j0.0.0549$$

then

$$V_1^{(3)} = 1.0117 + j0.0551$$

and the procedure has converged.

Therefore $V_1 = 1.013$ per unit at an angle of 3^0, i.e., the voltage at the generator terminals is 1.3 percent above that at the source. The angle between the two voltage vectors is small (3^0).

(ii)

The current (I) in the circuit may be calculated from:

$I = S^*/V_1^* = (0.5 + j0.101)/(1.0117 - j0.0551) = 0.4873 + j0.1264$ per unit or 0.503pu.

With a connection voltage of 33 kV the base current is given by

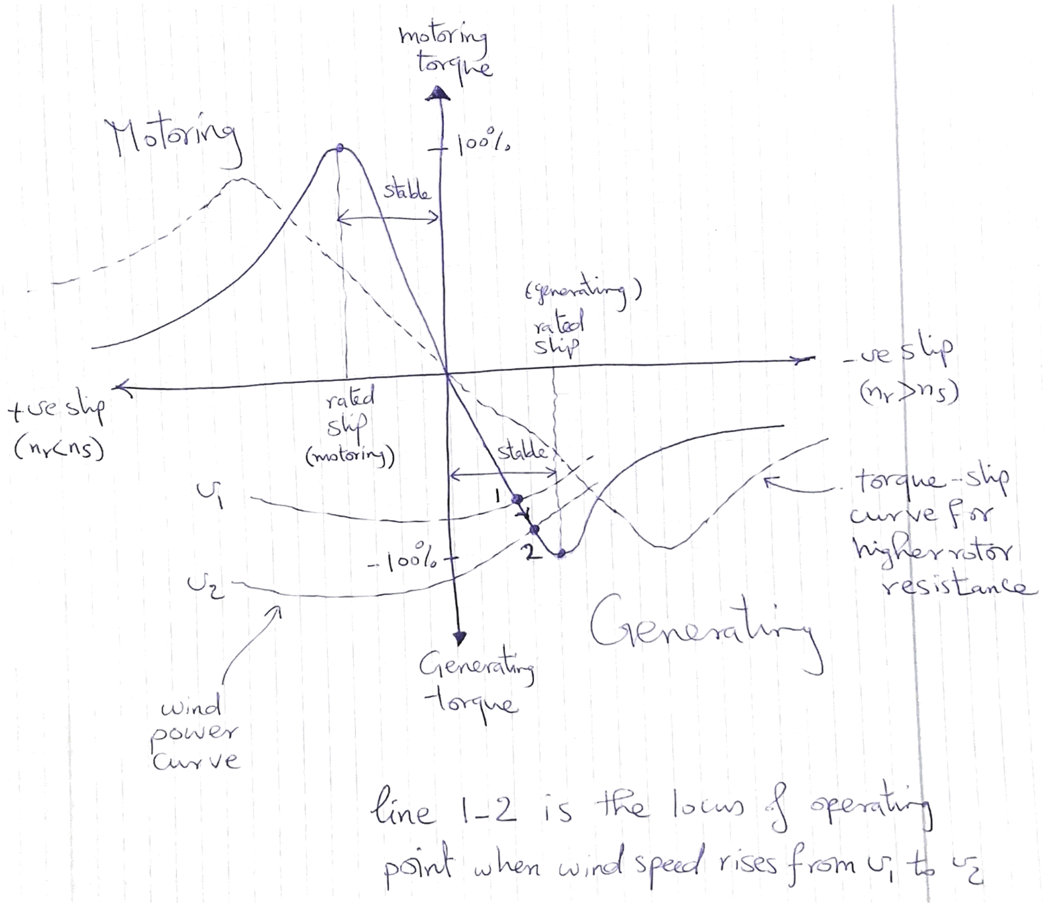
$I_{base} = S_{base}/sqrt(3)\, V_{base} = 5 \cdot 10^6/1.732 \cdot 33 \cdot 10^3 = 87.5$ A

Therefore, I = 0.503x87.5 = 44A

Power loss: $I^2R = 0.503^2x0.05=0.0127$ per unit

Q5

Note: rated slip points correspond to rated torque. Also note that in practice, the rated torque is designed lower than the peak torque in the curve to leave safe margin for overloading without going into unstable region.



Q6

a) $n_s = 120f/p = 120*50/250 = 24rpm$

b) At cut in wind speed:

$\lambda_{opt} = \omega_r*R/V_w \rightarrow \omega_r = Vw*\lambda_{opt}/R = 5*9/(130/2) = 0.692$ rad/s

$n_r = 60* \omega_r/ 2\pi = 60*0.692/6.28 = 6.61$ rpm

$f = p*n_r/120 = 250*6.61/120 = 13.77$ Hz

At rated wind:

$\lambda_{opt} = \omega_r*R/V_w \rightarrow \omega_r = Vw*\lambda_{opt}/R = 12*9/(130/2) = 1.662$ rad/s

$n_r = 60* \omega_r/ 2\pi = 60*1.662/6.28 = 15.875$ rpm

$f = p*n_r/120 = 250*15.875/120 = 33.07$ Hz

(Note that the frequency at wind speed 12m/s could have been obtained multiplying the frequency at 5m/s wind speed (13.77Hz) by the ratio of wind speed rise (12/5) since the WT operates at a constant value of tip-speed ratio at both wind speeds.