Department of Electrical Engineering
Indian Institute of Technology Bombay, Powai
EE238 : Power Engineering II
Solution to Assignment 1

1. Slip = $\frac{50-1.5}{50} = 0.03$. Synchronous speed $N_s = \frac{120\times50}{8} = 750$ r.p.m.
   Rotor speed $N = (1-s)N_s = 750 \times (1-0.03) = 727.5$ r.p.m

2. Rotor frequency $f_r = \frac{90}{60} = 1.5$ Hz. Rotor speed $N = \frac{120\times(50-1.5)}{6} = 970$ r.p.m.
   Output power $P = \omega_m \times T = \frac{2\pi\times976}{60} \times 162 = 16455.7$ W.
   B.H.P $= \frac{16455.7}{746} = 22.1$
   Mechanical power developed $P_m = (162+13.5) \times 2\pi\frac{970}{60} = 17826.9$ W
   Rotor Cu losses $= \frac{P_m s}{1-s} = 550$ W where $s = \frac{1.5}{50} = 0.03$
   Input = 17826.98 + 550 +750 = 19.2 kW. Effeciency = 85.71 %.

3. Assume star connected stator. $V_{ph} = 500/\sqrt{3} = 289$ V. $X_m = 289/36 = 8\Omega$.
   $R_c = V^2/P_c = 166.71\Omega$
   Input Imedance $= ((0.062 + \frac{0.062}{0.02}) + j(0.21+0.21))||\frac{jX_mR_c}{jX_m+R_c} = 2.8\angle27.66°$
   Stator current $I_s = \frac{288.86}{2.8\angle27.66°} = 103.1\angle{-27.66°}$
   Power factor $= \cos(28°) = 0.89$ lag
   Rotor current $= \frac{288.68}{(0.062+0.062/2)+j(0.21+0.21)} = 90.52\angle{-7.57°}$
   Rotor input per phase $= P_e = (90.52)^2\frac{0.062}{0.02} = 25402.2$ W
   Mech. power output per phase $= P_m = 25402.2 \times (1-0.02) = 24894$ W
   Output $= 3 \times 24894 - 750 = 73932$ W $= 99$ h.p
   Input power $= \sqrt{3} \times 500 \times 103 \times 0.89 = 79465$ W
   Efficiency $= \frac{73932}{79465} = 93\%$

4. Output=$50 \times 746 = 37300$ W. Input = $37300/0.9 = 41444$ W. Total loss = 4144 W.
   Let iron loss =W_i, Stator copper loss = Rotor copper loss = W_c
   No load loss = Iron loss + Windage + Friction loss.
   $3 \times$ Mech. losses = W_i + Mech loss. Therefore, Mech loss = $\frac{W_i}{2}$
   Total loss = Stator Cu. loss + Rotor Cu. loss + Iron loss + Mech loss
   $4144 = W_i + W_i + W_i + W_i/2$
   Therefore $W_i = 1184$ W
   Rotor input = Stator input - Stator Cu loss - Iron loss = 39076 W
   % Slip = $\frac{\text{Rotor Cu loss}}{\text{Rotor Input}} = \frac{1184}{39076} \times 100 = 3.03\%$

5. Synchronous speed = 1000 r.p.m. Slip = 0.05, $P_m = 30 \times 746 = 22350$ W
   Rotor Cu loss = $\frac{22380 \times 0.05}{1-0.05} = 1178$ W
   Input = $\frac{22380}{1-0.05} + 2000 = 25.6kW$
   % Efficiency = $\frac{(30-2)\times 746}{25600} \times 100 = 82\%$
   $I_L = \frac{25600}{\sqrt{3}\times 550 \times 0.08} = 30.48$ A
   Rotor frequency = $sf_s = 0.05 \times 50 \times 60 = 150$ cycles per min.

6. Rotor resistance referred to stator = $R'_r = 0.1 \times 1.75^2 = 0.306\Omega$
   Rotor reactance referred to stator = $X'_r = 2.576\Omega$
   Rotor current $I'_r = \frac{220/\sqrt{3}}{\sqrt{(\frac{0.306}{0.05})^2 + (2.576)^2}} = 18.72$ A
   Total rotor input (airgap power) = $3I'^2_r \frac{R'_r}{s} = 6574.3$ W
   Total torque = $T = \frac{P_2}{2\pi n_s}$ where $n_s = \frac{1500}{60}$ which gives T = 41.9 Nm
   Rotor losses are not given, assume zero.
   HP = $\frac{6574 \times (1-0.05)}{746} = 8.37$
   Slip at max. torque = $\frac{R'_r}{X'_r} = 0.111$
   Max torque = $\frac{3V_1^2}{4\pi n_s X'_r} = 56$ Nm
   Speed at max. torque = $N_s \times (1 - 0.111) = 1333$ rpm

7. $s = \frac{1000-975}{1000} = 0.025$. Rotor input = 40 - 1 = 39 kW.
   Rotor Cu loss = $sP_2 = 0.025 \times 39 \times 10^3 = 975$ W
   $P_m = 39 \times (1 - 0.025) = 38.03$ kW. Shaft HP = $\frac{38.03-2}{0.746} = 48.3$
   % Efficiency = $\frac{36.025}{40} = 90\%$

8. $N_s = \frac{120 \times 50}{12} = 500$ r.p.m.
   Total resistance of the machine = $\frac{100 \times 10^3}{2 \times 250^2} = 0.53\Omega$

Rotor equivalent resistance $= 0.27\Omega$

$T = \frac{3I_r'^2 R_r'}{2\pi N_s \times s}$

Starting torque $= \frac{3I_r'^2 R_r'}{2\pi N_s} = 955$ Nm

9. $s_{max} = \frac{750-630}{750} = 0.16$, $s_{max} = \frac{R_r'}{X_r'}$

   $X_r' = 0.4375\Omega$. s_{max} should be equal to 1 implies that $X_r' = R_r' + R_{ext}$

   $R_{ext} = 0.37\Omega$

10. Core loss = 4.2 kW. No load p.f $= \frac{4200}{\sqrt{3}\times 460\times 40} = 0.13$

    $R_o = \frac{460/\sqrt{3}}{40\times 0.13} = 51\Omega$

    $X_m = R_o/\tan\theta = 6.7\Omega$, $R_{eq} = \frac{8\times 10^3}{3\times 140^2} = 0.136\Omega$

    $Z_{eq} = \frac{100}{\sqrt{3}\times 140} = 0.412\Omega$, $X_{eq} = 0.389\Omega$ so $X_r' = 0.19\Omega$

    $R_s = R_r' = 0.068\Omega$, $N_s = 900$ rpm, $s = \frac{900-873}{900} = 0.03$, $\frac{R_r'}{s} = 2.27\Omega$

    $Z_{eq} = [(2.27 + 0.068) + j0.389]||\frac{j51\times 6.7}{51+j6.7} = 2.04\angle 27°$

    $I_1 = \frac{460}{\sqrt{3}\times 2.04\angle 27°} = 130\angle{-27°}$ A

    Power input $= 3 \times \frac{460}{\sqrt{3}} \times 130 \times \cos -27° = 92.42$ kW

    Stator Cu loss $= 3 \times 130^2 \times 0.068 = 3458$ W, Air gap power = 92.42 - 3.458 - 4.2 = 84.76 kW

    Rotor Cu loss $= 84760 \times 0.03 = 2543$ W, $P_m = 82217$ W

    Power output = 82217 - 1000 = 81217 W.

    %Efficiency $= \frac{81217}{92420} = 87.8\%$

11. Starting current taken from the supply with DOL $= \sqrt{3} \times \frac{500}{\sqrt{3}} = 248$ A

    Star-delta starting, phase voltage $= \frac{500}{\sqrt{3}}$, starting current $= \frac{289}{3.5} = 82.5$ A

12. $I_r' = \frac{230}{\sqrt{(\frac{1}{2})^2+1}}$, Total $P_m = \frac{3(1-s)\times 230^2 s^2}{s(1+s^2)}$

    Total load torque $= 33.68 \times \frac{N}{N_s}$ where $N = N_s(1-s)$

    With mechanical loss neglected, $\frac{P_m}{2\pi N_s(1-s)/60} =$ Total load torque

    Solving for s gives, $s = 0.063$ and $N = 3000(1-s) = 2810$ rpm

13. kVA = 15, p.f =0.6,$\sin\phi = 0.8$

    Real power = 9 kW, Reactive power = 12 kVAR

    Improvement of power factor leaves P unchanged. Q reduces to Q_1.

    Reduction in $Q = 12 - \frac{9\times 0.6}{0.8} = 5.25$ kVAR

Per phase reduction in $Q = \frac{5.25}{3} = 1750$ VAR
$\frac{V^2}{X_c} = 1750$ with $V = 230$V, value of C is 105μF