Q1. (35 points):

A 3phase, 6-pole, 480V, 60Hz, induction motor has the following parameters:

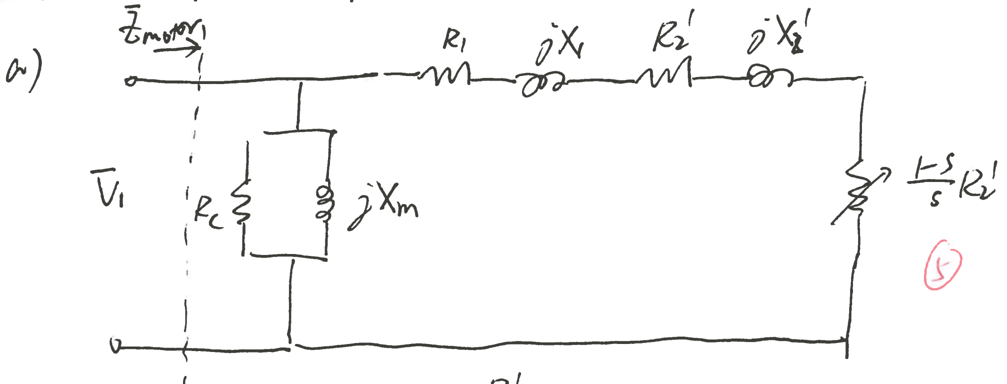
$$R_1 = R_2' = 0.3\ \Omega,\ X_1 = X_2' = 1\ \Omega,\ X_m = 100\ \Omega,\ R_c = 250\ \Omega$$

This motor is to be used to drive a load with a constant torque of 60 Nm independent of speed. *You may use the approximate equivalent for the induction motor with the shunt branch connected across the source to answer the following questions.*

20 a) What is the starting current and torque of this machine when it is started with rated voltage?

15 b) At what speed and slip will the motor run?

a)



$$T_{shaft} = \frac{3P}{2\omega_e} \frac{|V_1|^2 \cdot \frac{R_2'}{s}}{\left[(R_1 + \frac{R_2'}{s})^2 + (X_1 + X_2')^2\right]} \quad (5)$$, where $|V_1| = \frac{480}{\sqrt{3}} = 277.1V$

$$T_{start} = T_{shaft}\Big|_{s=1} = \frac{3P}{2\omega_e} \frac{|V_1|^2 R_2'}{(R_1+R_2')^2 + (X_1+X_2')^2}$$

$$= \frac{3\times 6}{2\times 120\pi} \cdot \frac{277.1^2 \times 0.3}{(0.3+0.3)^2 + (1+1)^2} = \frac{549.9}{4.36} = \boxed{126.2\ Nm} \quad (5)$$

To obtain starting current, we compute an equivalent motor impedance looking from source.

$$\bar{Z}_{motor} = (jX_m) \| R_c \| [R_1 + R_2' + j(X_1+X_2')] = (j100) \| 250 \| (0.6+j2) = 0.5907 + j1.9550$$

$$\bar{I}_{start} = \frac{\bar{V}_1}{\bar{Z}_{motor}} = \frac{277.1}{0.5907+j1.9550} = 135.68\angle -73.19^\circ \quad |\bar{I}_{start}| = \boxed{135.68\ A} \quad (5)$$

b)

$$T_{shaft} = \frac{549.9 \cdot \frac{1}{s}}{(0.3 + \frac{0.3}{s})^2 + 4} = 60 \Rightarrow 4.09s^2 - 8.985s + 0.09 = 0 \quad (5)$$

$$\boxed{s = 0.010} \quad (5) \qquad n_s = \frac{120f}{P} = 1200\ rpm \qquad n_m = (1-s)n_s = \boxed{1188\ rpm} \quad (5)$$

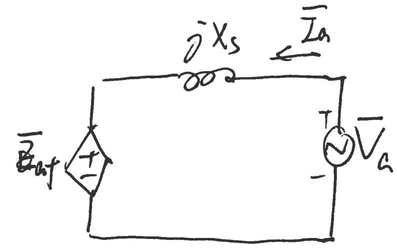
Q2. (35 points):

A 480 Volt (line-line rms), Y-connected, 4-pole, 60Hz, wound-field synchronous motor is drawing 30 Amps at 0.9 leading power factor from a 480 Volt (line-line rms) power system. The field current flowing under these conditions is 12 Amps. The motor synchronous reactance is 2 Ω. You may ignore armature resistance.

15 a) Find the internal voltage and torque angle for this condition.

10 b) Draw the phasor diagram for this condition. On the same axis, use dashed lines to show the phasors for unity power factor operation while consuming the same amount of real power.

10 c) How much field current would be required to make the motor operate at unity power factor while consuming the same amount of real power?



(5)

a) $\bar{V}_a = \frac{480}{\sqrt{3}} \angle 0^\circ = 277.1 \angle 0^\circ$

$\theta = \langle \bar{V}_a, \bar{I}_a \rangle = -\cos^{-1}(0.9) = -25.84^\circ$

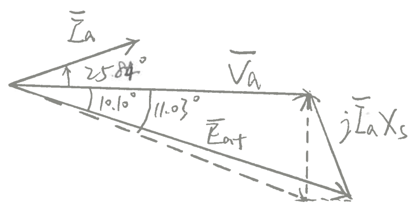
$\bar{I}_a = |\bar{I}_a| \angle -\theta = 30 \angle 25.84^\circ$ (5)

$\bar{E}_{af} = \bar{V}_a - j\bar{I}_a X_s = 277.1 \angle 0^\circ - j \cdot 30 \angle 25.84^\circ \times 2$

$= 303.2 - j54.0 = 308.0 \angle -10.10^\circ$ (5)

$|\bar{E}_{af}| = \boxed{308.0}$ ✓, $\delta = \boxed{-10.10^\circ}$

b)



(10)

c) $|\bar{I}_a| = 30 \times 0.9 = 27$ A , $\bar{I}_a = 27 \angle 0^\circ$

$\bar{E}_{af} = \bar{V}_a - j\bar{I}_a X_s = 277.1 \angle 0^\circ - j\,27 \times 2$

$= 282.3 \angle -11.03^\circ$ (5)

$I_f = \frac{282.3}{308.0} \times 12 = \boxed{11.00\ A}$ (5)

Q3. (30 points):

a) A synchronous generator is connected to the grid at rated voltage. A system fault occurs dragging the machine terminal voltage to 0.25 p.u. After a short period, the terminal voltage is restored to 0.9 p.u. No action is taken at the generator (i.e. the mechanical load and the excitation remain constant). Sketch the power versus load angle curves associated with this scenario and shade the areas needed to determine whether the synchronous generator would return to stable operation using the 'equal area criteria'.

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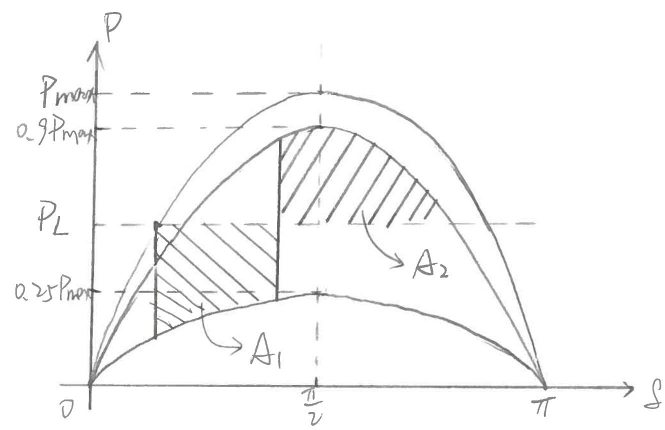

curves: 6 + 2 (P_L)

A_1: 4

A_2: 4

$A_2 > A_1$: 2

If $A_2 \geq A_1$, generator would return to stable operation.

b) A particular generator frequently experiences the scenario described above, and is barely able to ride through such transients. You have been tasked with identifying a new generator that is more stable under the same situation. List two parameters you would change in the generator design to achieve this, and briefly describe the impact.

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1). Small synchrons reactance X_s, or higher field back emf, E_{af}

This gives a higher maximum power, and allows a larger critical clearing angle δ_{cr} 3+3

2) Larger rotor inertia J

Larger J gives more time for the breaker to act for a given δ_{cr}.

The relationship between t_{cr} and δ_{cr}:   3+3

$$t_{cr} = \sqrt{\frac{(\delta_{cr} - \delta_0)}{\frac{\omega_s}{4H} P_m}}$$