THE UNIVERSITY OF BRITISH COLUMBIA

Department of Electrical and Computer Engineering

EECE 373: Electromechanical Energy Conversion and Transmission

Fall 2014

Practice Final Exam

Magnetic Circuits; Electromechanical energy conversion; Single and three-phase transformers; DC Machines; Induction Machines; Round and Selient Rotor Synchronous Machines, and Reluctance Stepper Motors

Surname:_____

First Name:_____

Student ID:_____

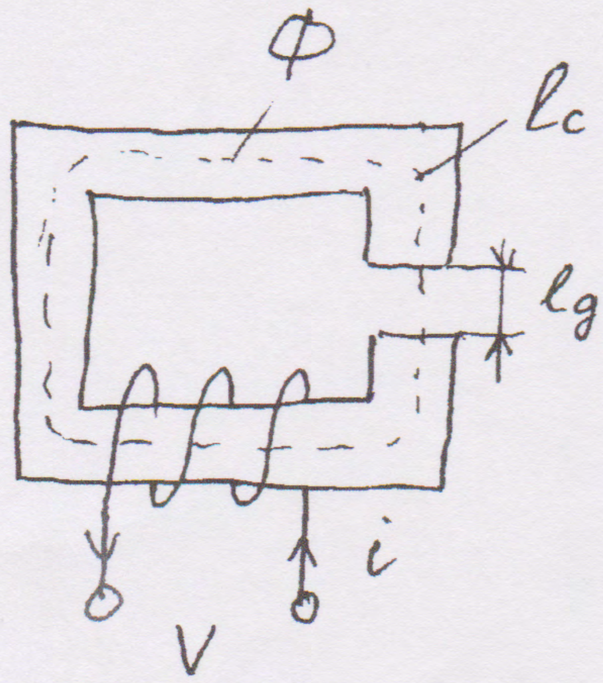
Signature:_____

Problem	Points	Max.
1		
2		
3		
4		
5		
6		
7		
Total		100

- **Close notes and books.**
- You are allowed to have only a **calculator** and a **pen/pencil**.
- Show you work including **derivations**, **comments**, **assumptions**, and **units** wherever appropriate.
- Use back side of each page or ask for additional pages if you need extra space to write your answers.
- Exams suspected of cheating and/or turned in late will not be marked – **failed exam**.
- Cheating may result in your suspension and/or withdrawal from the university
- You have **90** minutes to answer the following questions:

Problem 1 (20pts)

Consider the magnetic system shown below. The core and air-gap have reluctances are $\Re_c = 0.5\times10^6\ A\cdot turn/Wb$ and $\Re_g = 4.5\times10^6\ A\cdot turn/Wb$, respectively. Neglect flux leakage, fringing, and core losses. The coil has 400 turns and the dc resistance of $5\,\Omega$.



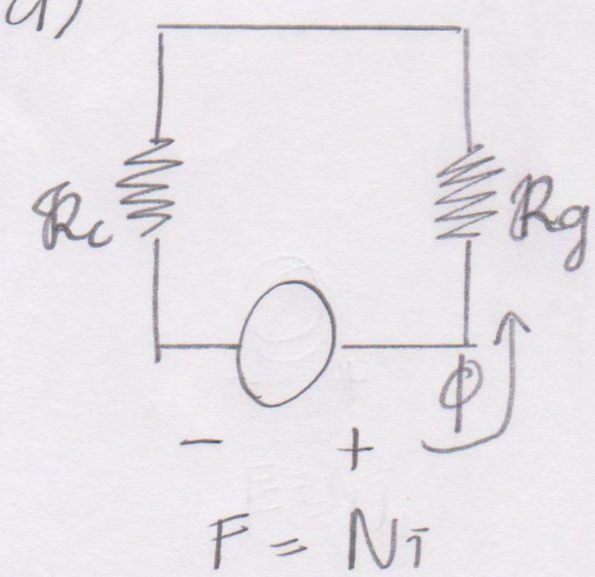
(a) (5pts) Draw an equivalent **magnetic** circuit, show the direction of mmf F and the flux Φ

(b) (5pts) Draw an equivalent **electric** circuit and sketch the corresponding qualitative phasor diagram assuming ac source (show all phasors & angles)

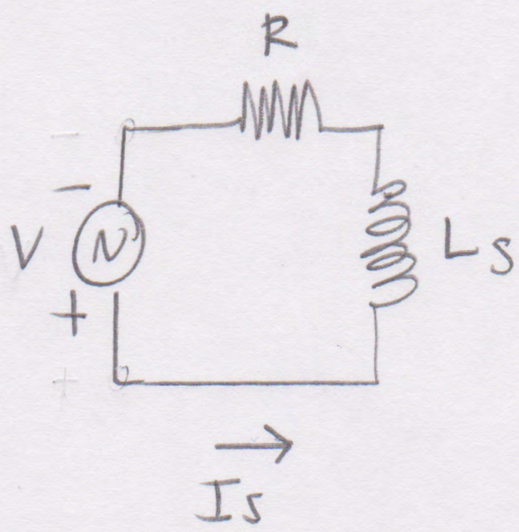
(c) (5pts) Calculate the inductance L

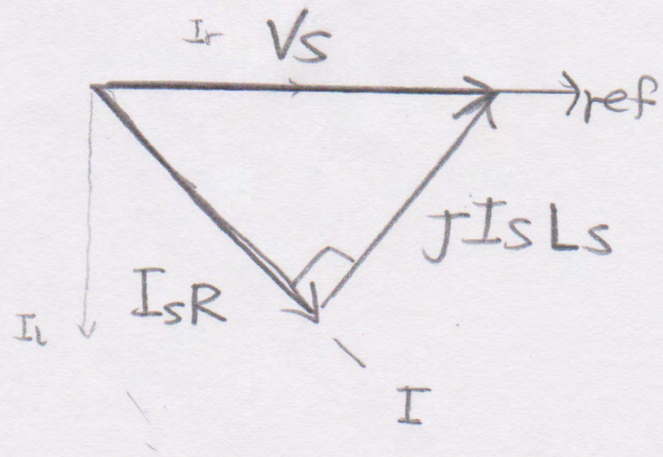
(d) (5pts) Calculate the coil impedance Z at 60Hz ac

a)



b)





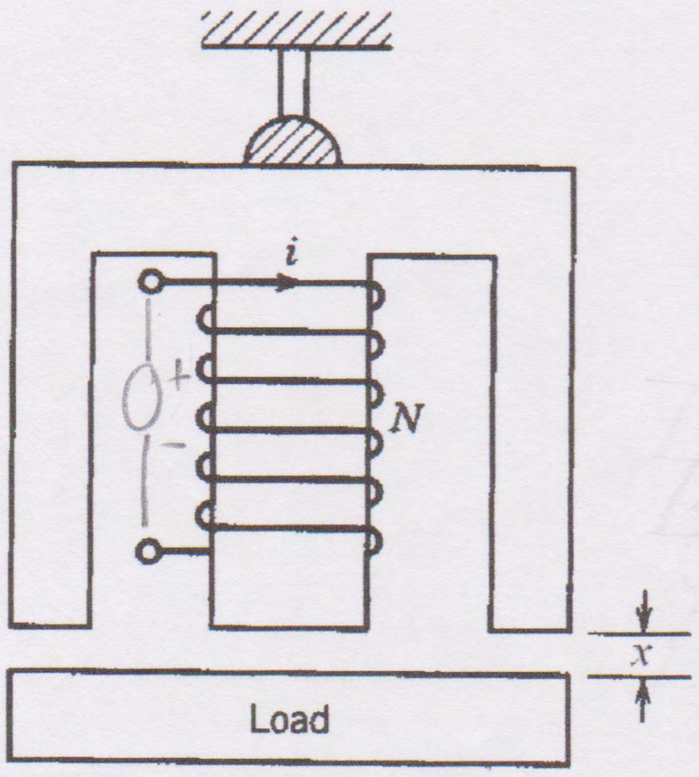
c) $$L = \frac{N^2}{\Re_c + \Re_g} = \frac{400^2}{(0.5E6)+(4.5E6)} = 0.032\ H$$

d) $$Z = R + j\omega L$$
$$Z = R + j(2\pi f)L$$
$$Z = 5 + j(2\pi)(60)(0.032)$$
$$Z = 5 + j\,12.06\ \Omega$$

Problem 2: (20pts)

Consider an electro-mechanical lifting device shown in the figure. You can use common approximations as we did in class and assume magnetically-linear core. The air-gap between the core and the plunger is denoted by x (which has units of meters). Assume that total inductance of this device may be approximated as

$L(x) = 0.2 + \dfrac{5 \cdot 10^{-3}}{x}$ H, and the dc resistance r is $10\,\Omega$.

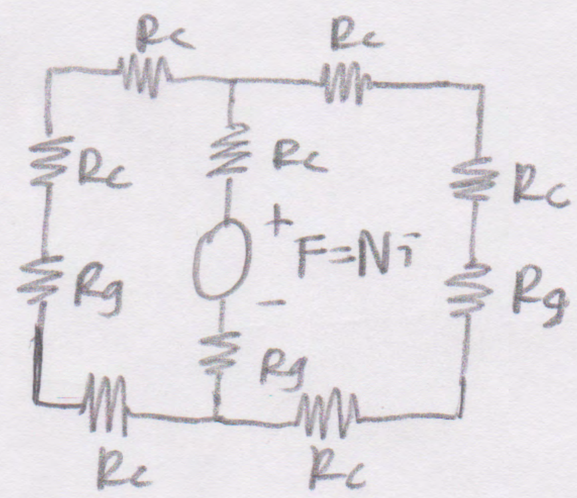


(a) (5pts) Sketch the equivalent **magnetic** circuit and label all elements

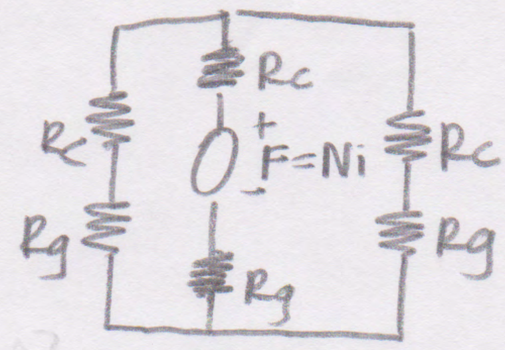
(b) (5pts) Sketch the equivalent **electric** circuit and label all elements

(c) (10pts) The device is used to lift a 5kg load from a distance of 5 mm. What value of dc voltage V_{dc} and dc current I_{dc} should be applied to the coil?

a)

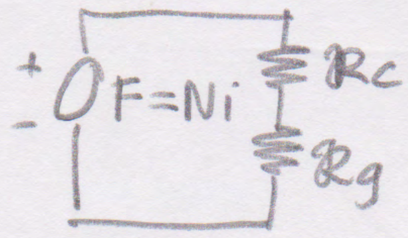


$\Rightarrow$



$\Downarrow$

essentially simplifies to



b)

c) $\Delta W_m = 5(9.81) \times 5E{-3} = 0.25$

$L(x) = 0.2 + \dfrac{5 \times 10^{-3}}{x}$ $\quad R = 10$

$W_f = \frac{1}{2} L(x_1)\,dx\; i^2$

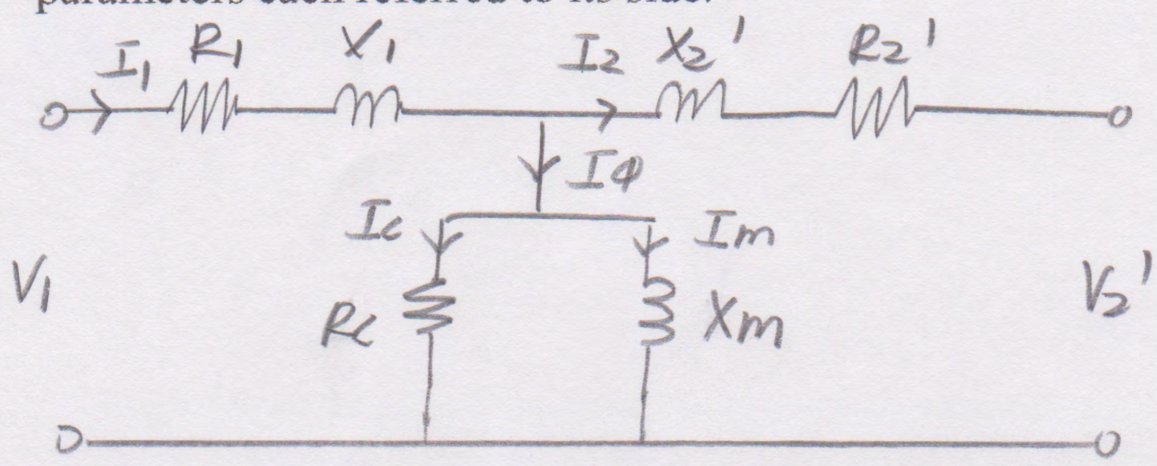
$= \frac{1}{2} L(\Delta x)\, i^2$

$i = \sqrt{\dfrac{2W_f}{L\Delta x}}$ $\quad W_f = W_m$

Problem 3 (20pts)

Consider a single-phase 60Hz, 120/24V step-down transformer. The results of the open-circuit and short-circuit tests are: $V_{1,oc} = 120V$, $I_{1,oc} = 1A$, $P_{1,oc} = 20W$, and $V_{1,sc} = 20V$, $I_{1,sc} = 10A$, $P_{1,sc} = 50W$

Assume that winding resistances and leakage reactances are respectively equal when referred to the same side, $R_1 = R_2'$ and $X_1 = X_2'$. You may use common assumption as we did in class. Calculate the equivalent circuit parameters each referred to its side.



$$a = \frac{120}{24} = 5$$

OC →

$$R_c = \frac{V_{oc}^2}{P_{oc}} = \frac{120^2}{20} = 720\ \Omega \quad I_c = \frac{V_{oc}}{R_c} = \frac{120}{720} = 0.1666 = 0.167\ A$$

$$I_m = \sqrt{I_{oc}^2 - I_c^2} = \sqrt{1^2 - 0.166^2} = 0.968013 = 0.968\ A$$

$$X_m = \frac{V_{oc}}{I_m} = \frac{120}{0.968013} = 121.7022 = 121.7\ \Omega$$

SC →

$$R_{eq} = \frac{P_{sc}}{I_{sc}^2} = \frac{50}{10^2} = 0.5\ \Omega \quad Z_{eq} = \frac{V_{sc}}{I_{sc}} = \frac{20}{10} = 2\ \Omega$$

$$X_{eq} = \sqrt{Z_{eq}^2 - R_{eq}^2} = 1.7320$$

so...

$R_{eq} = R_1 + R_2'$ but $R_1 = R_2'$ so... $2R_1 = 0.5$

$R_1 = 0.25\ \Omega = R_2'$

$$R_2' = a^2 R_2 \Rightarrow R_2 = \frac{R_2'}{a^2} = 0.01\ \Omega$$

and $X_{eq} = X_1 + X_2' = 1.7320$

but $X_1 = X_2'$ so... $2X_1 = 1.7320$

$X_1 = 0.866\ \Omega = X_2'$

$$X_2' = \frac{X_2}{a^2} = 0.03464 = 0.0346\ \Omega$$

$$P_{3\phi} = 3 \cdot V_{1,ph} \cdot |I_{1,ph}| \cdot \underbrace{\cos\varphi}_{pf}$$

Problem 4: (20pts)

Assume that you have three identical step-down transformers shown on the figure below with $N_1 = 300$ and $N_2 = 100$. The transformers may be assumed ideal and connected into Δ/Δ. The load is composed of series *R-L* ($R = 8\,\Omega$ and $X = 6\,\Omega$) per-phase, which are Y-connected and balanced. The primary side is connected to a 3-phase 208V (line-to-line) balanced source. All voltages are **rms** values.

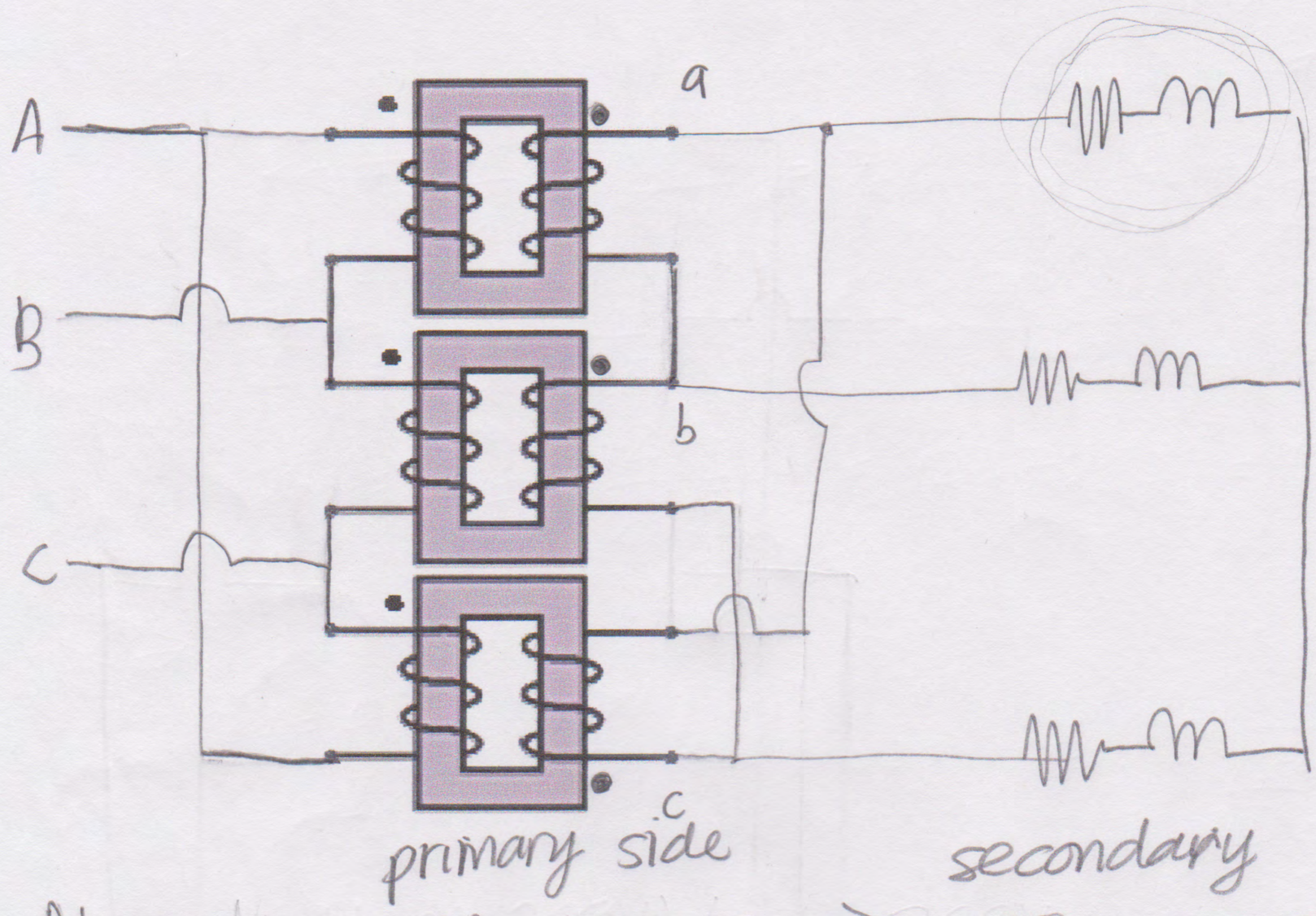
a. (3pts) Label the polarity of each secondary winding with dot "•". (Hint: note the direction of each winding!)

b. (5pts) Sketch the connection of the windings and the load resistors and inductors right on this figure below.

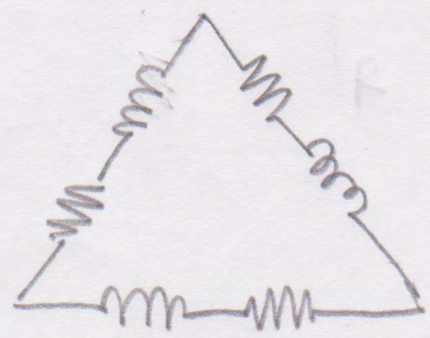
c. (2pts) Label the input primary side terminals (on your left) with ***ABC*** and the output terminals (load side on your right) with ***abc***.

d. (5pts) Calculate the **total three-phase real and reactive power** $P_{3\phi}$ and $Q_{3\phi}$ supplied to the load

e. (5pts) Calculate the **primary (input) line** current I_1 and its power factor angle in degrees



→ converting this to Δ



$\frac{N_1}{N_2} = 3$ $\quad V_{LtoL}\ 208V \Rightarrow \frac{208}{3} = 69.333$

Δ

we want V_φ

$V_{ph} = V_L$

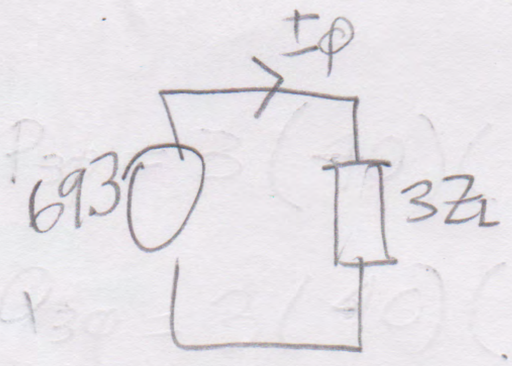
$I_{ph} = \frac{I_L}{\sqrt{3}}$

$P_{3\varphi} = 3 V_\varphi I_\varphi = \sqrt{3} V_L I_L \quad I_L = ?$

$P_{3\varphi} = \sqrt{3} V_L \cdot I_L$ real

$Q_{3\varphi} = \sqrt{3} V_L \cdot$ Imag (I_L)

Per φ eq ⇒ $\quad I_{ph} = \frac{V_{ph}}{3Z_L}$



$I_L = \sqrt{3}\, I_{ph}$

$= \sqrt{3}\, \frac{V_{ph}}{3Z_L} = \frac{69.3}{\sqrt{3}(8+6j)}$

Problem 5 (20pts)

Consider a **Permanent-Magnet DC motor** with the following parameters: nominal voltage $V_a = 24$ V; armature resistance $R_a = 2\Omega$; torque constant $K_t = 0.122\left[\frac{N \cdot m}{A} \text{ or } \frac{V \cdot \sec}{rad}\right]$; no-load speed 1800 rpm.

(a) (5pts) Draw an equivalent circuit and appropriately label its elements

(b) (5pts) Calculate the no-load armature current $I_{a,nl}$, friction torque T_{fric}, and the total no-load power loss P_{nl_loss}.

(c) (5pts) Calculate the starting torque T_{start} when the motor is supplied with nominal voltage

(d) (5pts) Assume that the maximum current that can be drawn from the given 24V dc source is 6A. Calculate the smallest value of an additional resistor R_{start} that can be used to safely start this motor. Sketch the circuit

Problem 6 (20pts)

Consider a 115V series-connected DC motor with the following parameters: armature resistance $R_a = 1\Omega$; and field winding resistance $R_f = 2\Omega$. The motor is supplied from a dc source $V_t = 115\,\text{V}$ and is operating under nominal load at speed $n = 3000\,\text{rpm}$ drawing armature current $I_a = 5\,\text{A}$.

(a) (5pts) Draw an equivalent circuit

(b) (5pts) Calculate the induced back emf, E_a

(c) (5pts) Assuming friction torque is 5% of the developed torque, calculate the load torque T_m and efficiency η in %

(d) (5pts) Calculate the torque at zero speed (starting torque), T_{start}

Problem 7 (20pts)

Consider a 60Hz, 36V (line-to-line), Y-connected, NEMA Clsass B (Squirrel-Cage) Induction Motor with the following per-phase parameters: $R_1 = 0.1\Omega$, $R_2 = 0.2\Omega$, $X_1 = X_2 = 0.3\Omega$, and $X_m = 6\Omega$ (**all parameters and variables are referred to the stator**). The motor is supplied with the nominal (rated) voltage and is driving a mechanical load. The speed of the motor shaft is n = 864 rpm. You can neglect core and friction losses and use an approximate equivalent circuit. Recall that $T_e = 3\frac{1}{\omega_{syn}} \cdot (I_2)^2 \cdot \frac{R_s}{s}$. Determine the following:

(a) (10pts) Number of poles P and slip s

(b) (5pts) The input power factor PF and the total (3-phase) input real power

(c) (5pts) Total output mechanical power

Problem 8 (20pts)

Consider a 3-phase, 2-pole **Permanent Magnet Round-Rotor Synchronous Generator** with per-phase stator resistance and synchronous reactance $R_a = 0.1\Omega$ and $X_s = 2\Omega$, respectively. Assume that this generator operates at 60Hz, 24V (line-to-line), and outputs electric power $S_{3\phi} = 300VA$ to a load with 0.8 lagging power factor.

(a) (6pts) Sketch a phasor diagram and label the q- and d- axes, all relevant angles, and phasors

(b) (7pts) Calculate the induced voltage E_f and the rotor angle δ in degrees

(c) (7pts) Assume mechanical rotational losses $P_{mech_loss} = 20W$, calculate the efficiency η

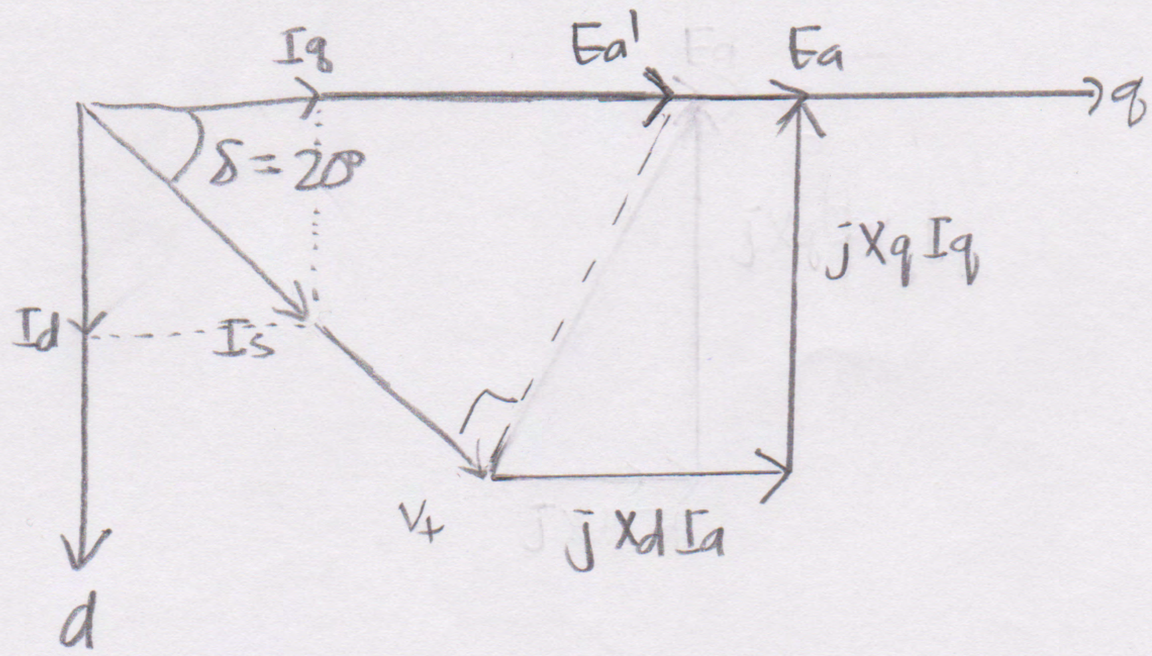
Problem 9 (20pts)

Consider a **Salient Pole Synchronous Machine**. The generator delivers rated (nominal) power at unity power factor and rated (nominal) terminal voltage and rotor angle $\delta = 20^\circ$. The generator open circuit voltage is 1.2pu. The stator resistance is negligible.

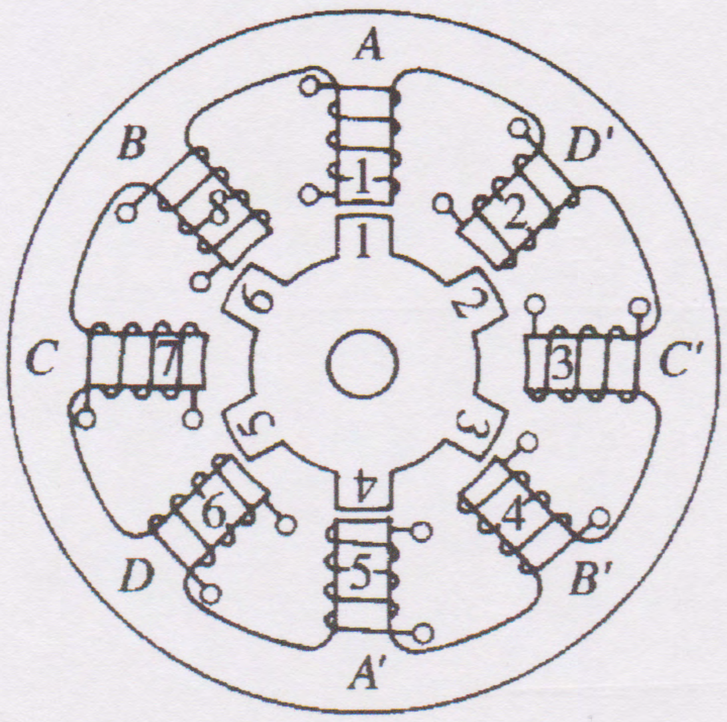
(d) (10pts) Sketch a phasor diagram and label the q- and d- axes, all relevant angles, and phasors

(e) (10pts) Calculate the reactances X_q and X_d in per unit

d)



Problem 10 (20pts)
Consider a single-stack stepper motor shown below. Complete the following table:



3pts	Stator tooth pitch (STP)	45°
3pts	Rotor tooth pitch (RTP)	60°
4pts	Step length $\Delta\Theta$	15°
3pts	Number of steps per revolution (Resolution)	24
3pts	Assume sequence of pulses as B – C – D – A, determine the direction of rotation (**CW** or **CCW**)	CW
4pts	Assume you have a 4-phase pulse generator to supply this motor. The generator produces 12 pulses per second per phase (48 pulses per second total). What is the motor speed in **rpm**?	120 rpm

n_{ST} = # stator teeth = 8

n_{rt} = # rotor teeth = 6

$STP = \frac{360°}{n_{st}} = \frac{360}{8} = 45°$

$RTP = \frac{360}{n_{rt}} = \frac{360}{6} = 60°$

$\Delta\theta = STP - RTP$
$= 60 - 45$
$= 15°$

so... $\frac{360}{15} = 24$ steps/rev

$24 \frac{steps}{rev}$ and $1 \frac{step}{pulse}$

so... $\frac{48 \text{ pulses}}{1 \text{ sec}} \times \frac{1 \text{ step}}{1 \text{ pulse}} \times \frac{1 \text{ rev}}{24 \text{ steps}} = 2$ rpsec

$60(2) = 120$