1) frame transformation

2) inductance - torque equation

3) inductance machine Vf control - simulink model

4) PM machine - understanding eq implementation

---

compensate the voltage

Problem 3 ②: peak value of phase voltage

③ $$\frac{V = \frac{400}{\sqrt{3}} \cdot \sqrt{2}}{60\ Hz} = Vf \text{ ratio}$$

$$\bar{V}_{\alpha\beta} = R\,\bar{i}_{\alpha\beta} + \frac{d\bar{\lambda}_{\alpha\beta}}{dt} \overset{s.s}{=\!=} R\,\bar{i}_{\alpha\beta} + j\,\omega_{el,rated}\,\bar{\lambda}_{\alpha\beta}$$

$\left(\frac{400}{\sqrt{3}} \cdot \sqrt{2}\right)$ rated condition $\to 0$ $\quad 2\pi \cdot 60$

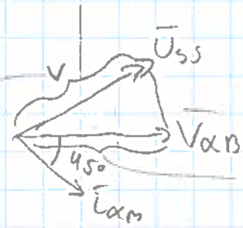
$\bar{V}_{\alpha\beta} = j\,\omega_{el,rated}\,\bar{\lambda}_{\alpha\beta}$ asking for $|\bar{\lambda}_{\alpha\beta}|$ = vector magnitude

$|\bar{V}_{\alpha\beta}| = |j| \cdot \omega_{e,rated}\,|\bar{\lambda}_{\alpha\beta}|$ ← cal. this

constant voltage / ω

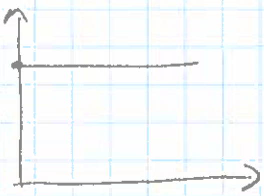
④ $f = 1\ Hz$

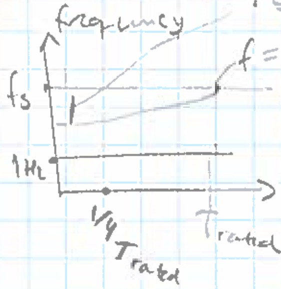
$V = \frac{|V_{rated}|}{f_{rated}} \cdot f$



asking this length

⑤



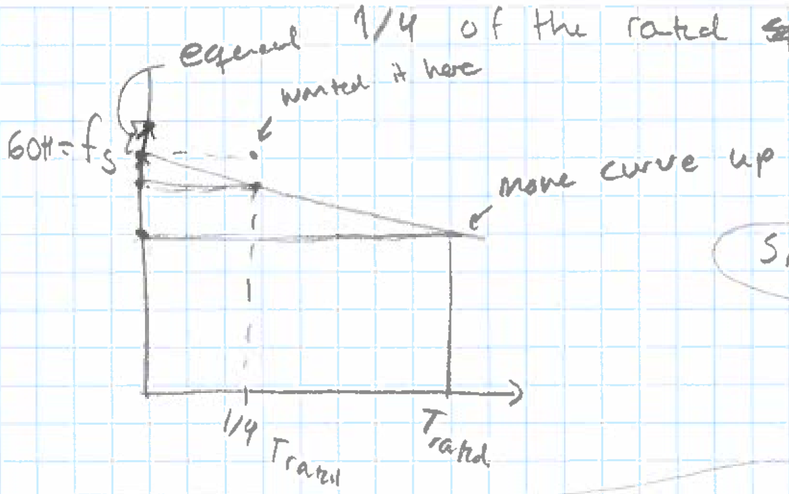


$f_s - f_r = s f_s$

$$s_{rated} = \frac{f_{s,rated} - f_{r,rated}}{f_{s,rated}}$$

$$f_{r,rated} = \underbrace{\frac{850}{60}}_{f} \cdot \underbrace{4}_{P}$$

1/4 of the rated ~~sep~~ slip frequen



$$S_{rated} = \frac{f_{s\,rated} - f_{r\,rated}}{f_{s\,rated}}$$

Torque equation

pole pairs

$$\tau = p \cdot i \cdot \lambda_{mpm} \cdot (-\sin\theta)$$

flux linking rotor and stator

$$\boxed{\tau = p \cdot i \cdot \frac{d(\lambda_{mpm} \cos\theta)}{d\theta}}$$

pm flux linkage from rotor

fundamental

DE STUDERENDES ERHVERVSKONTAKT

Course: Læseplan el

29/1 Date: 30/12 2017 Page: s.1

- Læs alle slides + noter på moodle
- Lav opgaver
- Få hjælp af Louise

- We have:
  - turns ratio transformation
  - Reference-frame transformation

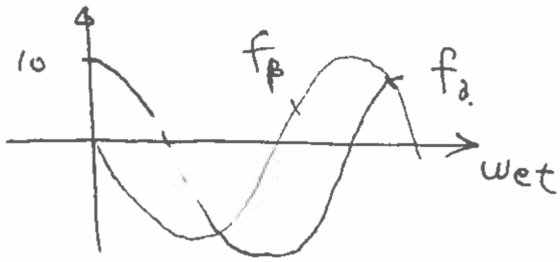
Answers – Exam 2014. Esbjerg.
Dynamic modeling of El. machines.

Problem 1.

(1) knowing $\bar{f}_{\alpha\beta} = f_\alpha + j f_\beta$ (the definition).

Now $\bar{f} = 10 e^{-j\omega_e t} = \bar{f}_{\alpha\beta}$

therefore: $\bar{f}_{\alpha\beta} = 10 e^{-j\omega_e t} = 10 [\cos(\omega_e t) - j \sin(\omega_e t)]$



(2) Using the "Vector projection method"

$$f_a = \text{Re}\left(\frac{\bar{f}_{\alpha\beta}}{e^{j0^\circ}}\right) = 10 \cdot \cos \omega_e t.$$

(take the real part) location of phas-a axis

$$f_b = \text{Re}\left(\frac{\bar{f}_{\alpha\beta}}{e^{j120^\circ}}\right) = 10 \cdot \cos(\omega_e t + 120^\circ)$$

location of phase-b axis

$$f_c = \text{Re}\left(\frac{\bar{f}_{\alpha\beta}}{e^{-j120^\circ}}\right) = 10 \cdot \cos(\omega_e t - 120^\circ).$$

What we find is that compared to a normal abc sequence, here, phase-b and phase-c are exchanged.

(4) We use the equation.

$$\bar{f}_{\alpha\beta} = \bar{f}_{abc} = \frac{2}{3}\left(v_a + v_b \cdot e^{j\frac{2\pi}{3}} + V_c e^{-j\frac{2\pi}{3}}\right)$$

$$= \frac{2}{3} \cdot V_{pk} \underbrace{\left[\sin(w_e t) + \sin\left(w_e t + \frac{2\pi}{3}\right) e^{j\frac{2\pi}{3}} + \sin\left(w_e t - \frac{2\pi}{3}\right) e^{-j\frac{2\pi}{3}}\right]}$$

The real part. of this term

$$= \sin(w_e t) + \sin\left(w_e t + \frac{2\pi}{3}\right) \cdot \cos\frac{2\pi}{3} + \sin\left(w_e t - \frac{2\pi}{3}\right) \cos\frac{2\pi}{3}$$

$$= \sin(w_e t) - \frac{1}{2} \cdot \left[\sin\left(w_e t + \frac{2\pi}{3}\right) + \sin\left(w_e t - \frac{2\pi}{3}\right)\right]$$

$$= \sin(w_e t) - \sin(w_e t) \cdot \cos\frac{2\pi}{3} = \frac{3}{2} \sin(w_e t)$$

The imaginary ~~park~~ part.

$$= \sin\left(w_e t + \frac{2\pi}{3}\right) \sin\frac{2\pi}{3} - \sin\left(w_e t - \frac{2\pi}{3}\right) \cdot \sin\frac{2\pi}{3}$$

$$= \frac{\sqrt{3}}{2} \cdot \left[\sin\left(w_e t + \frac{2\pi}{3}\right) - \sin\left(w_e t - \frac{2\pi}{3}\right)\right]$$

$$= \sqrt{3} \cdot \cos(w_e t) \cdot \sin\frac{2\pi}{3} = \frac{3}{2} \cos(w_e t)$$

Therefore.

$$\bar{f}_{\alpha\beta} = V_{pk} \cdot \frac{2}{3} \cdot \frac{3}{2} \cdot \left[\sin(w_e t) + j \cos(w_e t)\right]$$

$$= V_{pk} e^{j\left(w_e t - \frac{\pi}{2}\right)}$$

Then you can do the transformation to other reference frames using the vector projection method.

Problem 3 (10%)

A sketch of an induction machine phase axes is given below.

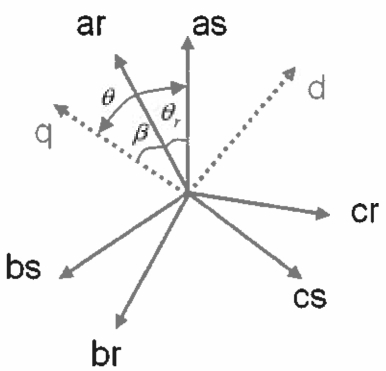


Fig. 3

where notation 's' stands for stator phase axes and notation 'r' stands for rotor phase axis.

Knowing the machine model expressed in an arbitrary qd-reference frame is

Stator side voltage equations:

$$\begin{bmatrix} u_{qs} \\ u_{ds} \\ u_{0s} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \cdot \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{0s} \end{bmatrix} + p \begin{bmatrix} \lambda_{qs} \\ \lambda_{ds} \\ \lambda_{0s} \end{bmatrix} - \omega_\theta \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \lambda_{qs} \\ \lambda_{ds} \\ \lambda_{0s} \end{bmatrix}$$

(1) Please transform this voltage equation into a vector form, using qd-frame space vector representations, i.e.

$$\overline{f}_{qd} = f_q - jf_d$$

(f is a variable that could stand for the voltage or current.)

(2) Please give the stator voltage equation when used for steady state performance analysis.

Problem 1 (20%)

For a given space vector $\bar{f} = 10e^{-j\omega_e t}$, where $\omega_e = 2\pi \cdot 50$, please

(1) Find the expressions for its corresponding afa-, beta-components. Please draw their waveforms as functions of the time.

(2) Find the expressions for its corresponding a-, b-, c-components. Please draw phase-a waveform as a function of the time.

(3) Now you are given a dq-reference frame. At time t=0, its d-axis is aligned with phase-a axis. It rotates positively (anti-clockwise direction), at a speed of $\omega_e = 2\pi \cdot 50$. Please find the expressions for the dq-components when the original space vector $\bar{f} = 10e^{-j\omega_e t}$ is transformed to this dq-reference frame. Please draw the dq-component waveforms as functions of the time.

(4) Transform the following three-phase signals (where $\omega_e = 2\pi \cdot 50$ [rad/s])

$$v_a = V_{pk}\sin(\omega_e t), \qquad v_b = V_{pk}\sin\left(\omega_e t + \frac{2\pi}{3}\right), \qquad v_c = V_{pk}\sin\left(\omega_e t - \frac{2\pi}{3}\right)$$

to a stationary afa-bet reference frame. Then transform the afa-bet signals to a rotating dq-frame. This dq-frame is rotating positively (anti-clockwise direction) at a frequency of 50 Hz.
(*Remember to give the expressions of the transformed signals.*)

Re eksamen esbjerg

Aug. 2014

Written examination in

Dynamic Models of Electrical Machines

Duration: 2 hours

- All usual helping aids are allowed, including text books, slides, personal notes, and exercise solutions
- Calculators and laptop computers are allowed, provided all wireless and wired communication equipment is turned off
- Internet access is strictly forbidden
- Any kind of communication with other students is not allowed
- Remember to write your study number on all answer sheets
- All intermediate steps and calculations should be included in your answer sheets --- printing the final result is insufficient

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The set consists of 2 problems

Problem 2 (25%)

A sketch of an induction machine phase axes is given below.

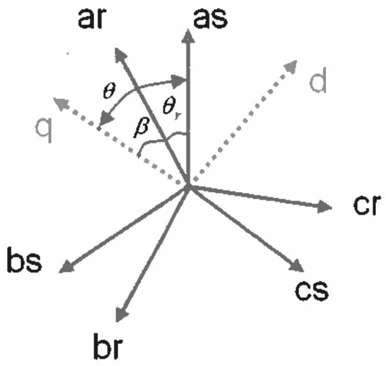


Fig. 1

where notation 's' stands for stator phase axes and notation 'r' stands for rotor phase axes.

Knowing the machine model expressed in an arbitrary qd-reference frame is

Stator side voltage equations:

$$\begin{bmatrix} u_{qs} \\ u_{ds} \\ u_{0s} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \cdot \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{0s} \end{bmatrix} + p \begin{bmatrix} \lambda_{qs} \\ \lambda_{ds} \\ \lambda_{0s} \end{bmatrix} - \omega_\theta \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \lambda_{qs} \\ \lambda_{ds} \\ \lambda_{0s} \end{bmatrix}$$

(1) Please re-express the above stator side voltage equations using αβ-reference frame. The α-axis is aligned with stator phase-as axis and the β-axis is leading phase-as axis by 90 electrical degrees (as usual).

(2) Please write down the stator side α, β flux linkage expressions.

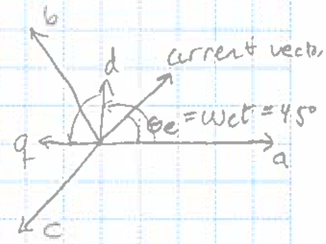
(3) Please sketch how you may implement the stator side voltage and flux linkage equations in Simulink in order to solve these equations. The input signals to your model are stator α, β voltage components and you want to solve the model to find the stator side α, β current components. Assuming all the rotor currents and rotor flux linkage components are known – you may use these rotor side variables directly in sketching your Simulink model. (*Like what we did in our last workshop day*).

Problem 1 (25%)

① A space current vector rotates at an angular velocity of $\omega_e = 2\pi \cdot 50$. Please tell what are the phase a, b, c current instantaneous values at a particular moment where the vector is found to be leading phase-a axis by 45 degrees. The amplitude of this current vector is 10 A

$I = 10$ A

$i_{abc} = 10\, e^{j45°}$



Instantantanious current at 45°

Phas a: $i_a = Re\left(\frac{10\, e^{j45°}}{e^{j0°}}\right) = 10 \cdot \cos(45°) = \underline{7.0711\ A}$

Phase b: $i_b = Re\left(\frac{10\, e^{j45°}}{e^{j120}}\right) = 10 \cdot \cos(45 - 120) = \underline{2.5882\ A}$

Phase c: $i_c = Re\left(\frac{10\, e^{j45}}{e^{j120}}\right) = 10 \cdot \cos(45 + 120) = \underline{-9.659\ A}$

② A dq-rotating reference is added to the figure. At a particular moment it is found that the d-axis is leading phase-a axis by 45 degrees. Please determine its instantaneous dq current component values

Vi har current vector som vi vil beskrive i dq-frame.

Tager $i_{abc} = 10\, e^{j45°}$ og gør i forhold til phase d and q

$$i_d = Re\left(\frac{10\, e^{j45°}}{e^{j90°}}\right) = Re\left(10\, e^{j(45-90)}\right) = 10 \cdot \cos(-45°) = \underline{7.071\ A}$$

$$i_q = Re\left(\frac{10\, e^{j45}}{e^{j180}}\right) = Re\left(10 \cdot e^{j(45-180)}\right) = 10 \cdot \cos(-135) = \underline{-7.071\ A}$$

③ Starting from the moment described in case ② after 0,05 sec. it is observed that now the d axis is leading the current vector by 90 degrees (før 45°) Please determine the rotating speed of this dq reference fram.

ω_r is dq frame rotation velocity

$\omega_e = 2\pi \cdot 50$ is angular velocity of current vector

$= 314,15$

Problem 1

(3) forsat: - we find the velocity from the equation of the different velocity between them - current and dq.

$\Delta\theta = 90 - 45 = 45^\circ$ } difference between velocity causes this
$t = 0{,}05$ sec

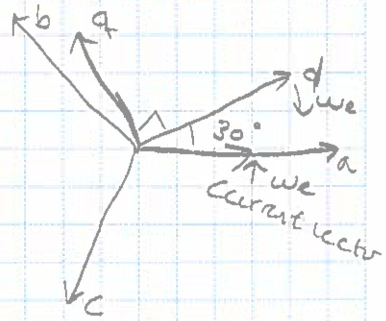
$(w_r - w_e)\cdot t = \Delta\theta$

$\frac{\pi}{6} + \frac{\pi \cdot 3}{2} = \frac{4\pi}{6} = \frac{2\pi}{3}$

$$w_r = \frac{\Delta\theta}{t} + w_e$$

$$w_r = \frac{45 \cdot \frac{2\pi}{360}}{0{,}05} + 314.15.. = \underline{329{,}867 \text{ rad/s}}$$

(4) Defining that at time $t=0$, the current vector is aligned with the phase-a axis and the d-axis is leading phase-a axis by 30 degrees. The current vector will start to rotate at an angular velocity of $\omega_e = 2\pi \cdot 50$ and the dq frame will start to rotate at angular velocity of $w_e = -2\pi \cdot 50$ (negativ)
Please sketch the d, q component wave formes for time periode $[0, 0.02]$ sec. $30^\circ = \pi/6$ rad



The d and q component is

$$i_d = Re\left(\frac{10\, e^{jw_e t}}{e^{j(w_e t - \pi/6)}}\right) = 10\, Re\left(e^{jw_e t} \cdot e^{j(w_e t - \pi/6)}\right)$$

$$= 10\, Re\left(e^{j(2w_e t - \pi/6)}\right) = 10\cos(2w_e t - \pi/6)$$

$$i_d = 10\cos(2 \cdot 2\pi \cdot 50 \cdot t - \pi/6)$$

$$i_q = 10\cos(2 \cdot 2\pi \cdot 50 \cdot t - \pi/6 - \pi/2) = 10\cos(4\pi 50 \cdot t - 2\pi/3)$$

$i_d(t=0) = 8{,}66$ $\qquad i_q(t=0) = -5$

$i_d(t=0{,}02) = 8.66$ $\qquad i_q(t=0{,}02) = -5$

Peak value: $1 = 10\cos(4\pi 50 \cdot t - \pi/6) \rightarrow t = \frac{1}{1200} + \frac{2\pi}{4\pi 50} = 0{,}0108$

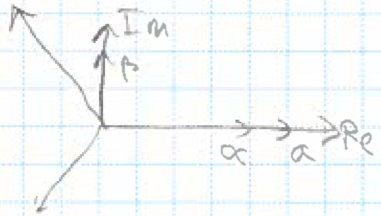
Peak value: $1 = 10\cos(4\pi 50\, t - 2\pi/3) \rightarrow t =$

Problem 1

(5) Please tell the relationship between the alfa-component in the $\alpha\beta$ reference frame and the phase a-component in abc frame. Give your proofs.

We have that for a system

for



And $\bar{f} = f_\alpha + jf_\beta$

So because α and a is both alined with the real axis must the a and α component are the same

→ Because they are allined there are no difference

Prove: Consider the space vector

$$\bar{f}_{\alpha\beta} = Ae^{j\omega t} = A(\cos\omega t + j\sin\omega t)$$

⇓

$$\bar{f}_\alpha = Re(\bar{f}_{\alpha\beta}) = \underline{A\cos\omega t}$$

$$\bar{f}_\beta = Im(\bar{f}_{\alpha\beta}) = A\sin\omega t$$

For phas a:

$$\bar{f}_a = Re\left(\frac{\bar{f}}{e^{j0^\circ}}\right) = \underline{A\cos\omega t}$$

proved

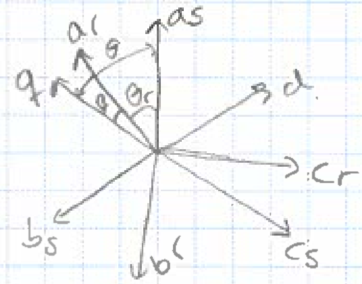
el.

$$\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/2 & \frac{\sqrt{3}}{2} \\ -1/2 & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} \rightarrow \underline{f_a = f_\alpha + 0 \cdot f_\beta = f_\alpha}$$

proved

Problem 2 (25%) Induction machine

A sketch of an induction machine phase axis is given



s = stator phase, r = rotor phase

q d o reference frame

① Please decribe how the mutual inductance between stator phase-a and stator phase-c is obtained?

The mutual inductance between as and cs is M_{ascs}

$$M_{ascs} = L_{aaq} Re\left(\frac{e^{j\theta}}{e^{j0°}}\right) \cdot Re\left(\frac{e^{j\theta}}{e^{-j2\pi/3}}\right) + L_{aad} Re\left(\frac{e^{j(\theta-\pi/2)}}{e^{j0°}}\right) \cdot Re\left(\frac{e^{j(\theta-\pi/2)}}{e^{-j2\pi/3}}\right)$$

$$M_{ascs} = L_{aaq} \cdot \cos\theta \cdot \cos\theta + 2\pi/3 + L_{aad} Re\left(e^{j\theta-\pi/2}\right) \cdot Re\left(e^{j(\theta-\pi/2+2\pi/3)}\right)$$

$$M_{ascs} = L_{aaq} \cdot \cos\theta \cdot \cos\theta + 2\pi/3 + L_{aad} \sin\theta \cdot \sin\theta + 2\pi/3$$

Der er måske mere - se facit fra daniela

② How the mutual inductance between the rotor phase-b and stator phase-a is obtained? br as - called M_{asbr}

The difference between stator and rotor is θ_r

$$M_{asbr} = L_{aaq} \cdot Re\left(\frac{e^{j\theta}}{e^{j0°}}\right) \cdot Re\left(\frac{e^{j\theta}}{e^{j(\theta_r+2\pi/3)}}\right) + L_{aad} \cdot Re\left(\frac{e^{j(\theta-\pi/2)}}{e^{j0°}}\right) \cdot Re\left(\frac{e^{j\theta-\pi/2}}{e^{j(\theta_r+2\pi/3)}}\right)$$

$$M_{asbr} = L_{aaq} \cdot \cos\theta \cdot \cos(\theta-\theta_r-2\pi/3) + L_{aad} \cos(\theta-\pi/2) \cdot \cos(\theta-\pi/2-\theta_r-2\pi/3)$$

Problem 2

(3) Suppose the rotor speed measured on the shaft is 240 rpm. The number of pole pairs of this machine is 4. Please calculate the value of rotor angular velocity ω_r to be used in this machine model.

$$p = 4$$

Rotor shaft speed $= 240$ rpms $= \omega_{r,mec}$

$$\omega_r = p \cdot \omega_{r,mec}$$

$$\omega_r = 4 \cdot 240 \cdot \frac{1}{60} \cdot 2\pi = 32\pi \text{ rad/s} \overset{\frac{1}{2\pi}}{=} 16 \text{ Hz} \to \frac{1}{s}$$

(4) Observed from fig 2 that when $\theta = 90°$, the d-axis is alligned with stator phase-a axis and the q-axis is leading phase-a by 90 degrees. Let's fix qd-frame at this position (let it become stationary). This make's d-axis now become alpha axis and $q \to \beta$.
Please give the machine stator and rotor voltage equations expresed in this alpha-beta frame. Leve zero component for simplicity

$$f_d = f_\alpha \quad , \quad f_q = f_\beta \quad , \quad \omega_0 = 0 \text{ - stationær } \alpha, \beta$$

First stator side voltage : $u_{\alpha s}$

replace d with α

-- " -- q with β

$$\begin{cases} u_{qs} = R_s \cdot i_{qs} + p \cdot \lambda_{qs} + \cancel{\omega_0} \lambda_{ds} \\ u_{ds} = R_s \cdot i_{ds} + p \lambda_{ds} - \cancel{\omega_0} \lambda_{qs} \end{cases}$$

$$\boxed{\begin{aligned} u_{\alpha s} &= R_s i_{\alpha s} + p \cdot \lambda_{\alpha s} \\ u_{\beta s} &= R_s i_{\beta s} + p \lambda_{\beta s} \end{aligned}}$$

! Der skal byttes rundt på α og β !

Rotor side : $u_{\alpha r}$

$$\begin{cases} u'_{qr} = R'_r i'_{qr} + p \lambda'_{qr} + (\cancel{\omega_0} - \omega_r) \lambda'_{dr} \\ u'_{dr} = R'_r i'_{dr} + p \lambda'_{dr} - (\cancel{\omega_0} - \omega_r) \lambda'_{qr} \end{cases}$$

$$\boxed{\begin{aligned} u'_{\alpha r} &= R'_r i'_{\alpha r} + p \lambda'_{\alpha r} - \omega_r \lambda'_{\beta r} \\ u'_{\beta r} &= R'_r i'_{\beta r} + p \lambda'_{\beta r} + \omega_r \lambda'_{\alpha r} \end{aligned}}$$

Problem 3

$p = 4$ pole pair induction machine

(1) Calculate the motors efficiency η at the rated operating condition and the rated shaft torque, rated slip

motor's efficiency = output power / input power

Output p. = 0,6 kW

$$\text{Input power} = \sqrt{3}\, V_L \cdot I_L \cdot \cos\theta = \sqrt{3} \cdot 400V \cdot 2{,}1A \cdot 0{,}6 = 872{,}95W$$

$$\eta = \frac{0{,}6\,kW}{0{,}872\,kW} \cdot 100 = \underline{68{,}73\%}$$

Rated shaft torque: $P_{ow} = \tau \cdot \omega \rightarrow \tau = \frac{P_{ow}}{\omega \leftarrow \text{rated speed}}$

$$\tau_{rated} = \frac{P_{spo}}{\omega_{r,mec,rated}} = \frac{600\,W}{850 \cdot \frac{1}{60} \cdot 2\pi\ rad/s} = \underline{6{,}74\,Nm}$$

Rated slip:

$$S_{rated} = \frac{\omega_{s,rated} - p \cdot \omega_{r,mec,rated}}{\omega_{s,rated}}$$

$$S_{rated} = \frac{60 \cdot 2\pi\ rad/s - 4 \cdot 850 \cdot \frac{2\pi}{60}\ rad/s}{60 \cdot 2\pi} = 0{,}055 = \underline{5{,}5\%}$$

(2) You will apply V/f control to this machine. The output of your V/f controller is the peak phase voltage command. What is the value of the constant V/f ratio you will use in your controller.

The ratio will be:

$$\cancel{\frac{400V \cdot \frac{1}{\sqrt{3}} \cdot \sqrt{2}}{60 \cdot 2\pi\ rad/s} = 0{,}8663\ Vs}$$

$$\frac{400\,V \cdot \frac{1}{\sqrt{3}} \cdot \sqrt{2}\ V}{60\,Hz} = 5.4433\ V/s$$

Course: Exam Jan. 2016

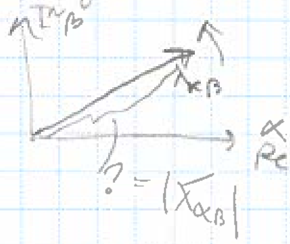
Date:

Page: s. 7 af

Problem 3

(3) At the rated operation condition please calculate the stator flux linkage magnitude. The resistance may be neglected

We have: we want $|\bar{\lambda}_{\alpha\beta}|$



$$\bar{V}_{\alpha\beta} = R\,\bar{i}_{\alpha\beta} + \frac{d\bar{\lambda}_{\alpha\beta}}{dt} \underset{}{\overset{s.s}{=}} j\,\omega_{elrated} \cdot \bar{\lambda}_{\alpha\beta}$$

$$|\bar{V}_{\alpha\beta}| = |j| \cdot \omega_{elrated} \cdot |\bar{\lambda}_{\alpha\beta}|$$

$$|\bar{\lambda}_{\alpha\beta}| = \frac{|\bar{V}_{\alpha\beta}|}{\omega_{elrated}} = \frac{400 \frac{1}{\sqrt{3}} V \cdot \sqrt{2}}{60 \cdot 2\pi \text{ rad/s}} = 0{,}866 \text{ Wb}$$

(4) Now it is asked to control the motor at 0,25 Hz (mechan shaft f) In order to maintain the same Stator flux level as experienced at the rated condition, compensation of the voltage drop on the stator resistance needs to be introduced to the V/f control. In steady state the phase-a current is found to be 1.0 A and phase-a current is lagging phase-a voltage by 45°. Please determine the magnitude of the phase voltage after phase resistive voltage drop compensation

$$f_{el} = p \cdot f_{mec} = 4 \cdot 0{,}25 \text{ Hz} = 1 \text{ Hz}$$

Stator resistance compensation; slip = 0

Control motor at running at 0,25 Hz

↳ Desired to maintain csf flux

The voltage is given as

$$V_s = r_s I_s \cos \overset{45°}{\theta} + \sqrt{V_{s\lambda}^2 - r_s^2 (I_s \cos\theta)^2} \quad (*)$$

$$V_{s\lambda} = \frac{V_{s\,rated}}{f_{s\,rated}} \cdot \underbrace{f_{s\,now}}_{\text{reference speed}}$$

$$V_{s\lambda} = 0{,}866 \text{ Vs} \cdot 4 \cdot 0{,}25 \cdot 2\pi \frac{\text{rad}}{s} = 5{,}44 \text{ V}$$

peak value $\rightarrow I_s = \hat{I}_a \cdot \sqrt{2} = \sqrt{2}$ $I_a = 1$ A

$$V_s = 12\,\Omega \cdot (\sqrt{2} \cdot 1 \cos(45) + \sqrt{0{,}866^2 - 12^2 (1 \cdot \sqrt{2} \cos 45)^2} = 12 + j\,11.968$$

Problem 3

(4) første matlab

$$|V_s| = abs(12 + j11,96) = 16.9485$$

The magnitude of the phase-a voltage is $|V_s| = 16,9485$.

(5) The stator frequency command is now 60 Hz and the machine is supplied with the rated voltage. When the machine is loaded by 1/4 of its rated load, please calculate the slip that needs to be added to the frequency command in order to make the shaft speed to be $60/4 = 15$ Hz (mechanical freq)

$$T_{e\,now} = \frac{1}{4} \cdot T_{e\,rated}$$

$$\frac{T_{e\,now}}{T_{rated}} = \frac{f_{se}}{S_{rated} \cdot f_{s\,rated}}$$

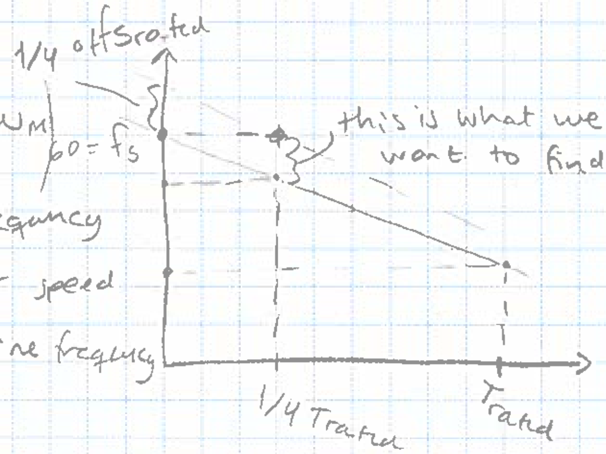
$$f_{se} = \frac{T_{now}}{T_{rated}} \cdot S_{rated} \cdot f_{rated}$$

$\omega_{se} = \omega_s - \omega_M$

ω_{se} - slip frequency

ω_s - stator speed

ω_M - machine frequency



$$f_{se} = \frac{\frac{1}{4} \cdot 6.74 \cdot 0{,}055 \cdot 60 \cdot 2\pi}{6.74} = 5{,}183 \text{ rad/s} = 0{,}825 \text{ Hz}$$

el.

$$f_{se} = \frac{1}{4} \cdot S_{rated} \cdot f_{s\,rated} = \frac{1}{4} \cdot 0{,}055 \cdot 60 = 0{,}825 \text{ Hz}$$

pga. $\omega_{se} = \omega_s - \omega_m \Rightarrow \omega_s = \omega_m + \omega_{se}$

is the slip frequency that needs to be added 0,825 Hz.

30 =

Problem 4: (25%) permanent magnet synchronous machine

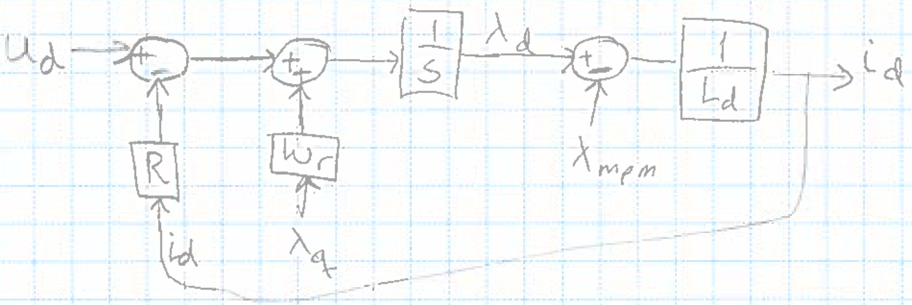
① Please show the block diagram as you may implement in simulink by using the d-axis voltage equation to solve for the d-axis current

Want to eliminate $p = d/dt$ to get $1/s$ instead

$$p\lambda_d = u_d + \omega_r \lambda_q - R i_d$$

$$\lambda_d = \frac{1}{s}(u_d + \omega_r \lambda_q - R i_d) \quad \& \quad \lambda_d = L_d i_d + \lambda_{mpm}$$

$$i_d = \frac{1}{L_d}(\lambda_d - \lambda_{mpm})$$



② If, at time $t=0$ in simulink you want the d-axis flux linkage λ_d to be equal to the rotor peak permanent magnet flux linkage λ_{mpm}. How can you achieve this in your Simulink model?

$\lambda_d = \lambda_{mpm}$ at $t = 0$

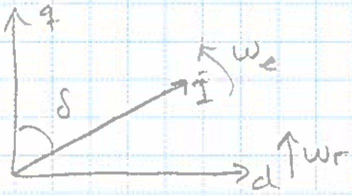
We have $\lambda_d = L_d i_d + \lambda_{mpm}$ so $i_d = 0$ should be

This is/can be achived by setting the initial condition of the integration block to be λ_{mpm}

Thus will $\lambda_d = \lambda_{mpm}$ at $t=0$ and $i_d = 0$

③ If I/f control of the PM machine should the current vector to be placed lagging the q-axis or should it be leading the q-axis? Please give your explanations

In I/f control of the PM machine the current vector should be lagging the q-axis. Let δ be the angle defined between current vector I and q-axis.



Problem 4

(3) forsat

The electro mechanical torque eq:

$T_e - T_{wad} = J$

se svar fra daniela - for uddybning

I lag inorder to get stable operation

(4) Se svar i faxict liste fra daniela

Written examination in

Dynamic Models of Electrical Machines and Control Systems

1st semester M.Sc. (PED/EPSH/WPS/MCE)

Duration: 4 hours

- All usual helping aids are allowed, including text books, slides, personal notes, and exercise solutions
- Calculators and laptop computers are allowed, provided all wireless and wired communication equipment is turned off
- Internet access is strictly forbidden
- Any kind of communication with other students is not allowed
- Remember to write your study number on all answer sheets
- All intermediate steps and calculations should be included in your answer sheets --- printing the final result is insufficient

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The set consists of 4 problems

Problem 2 **(25%)**

A sketch of an induction machine phase axes is given below (**same to the course slides**).

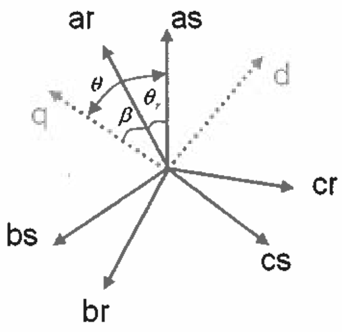

Fig. 2

where notation 's' stands for stator phase axes and notation 'r' stands for rotor phase axis.

(1) Please describe how the mutual inductance between stator phase-a and stator phase-c is obtained?

(2) How the mutual inductance between the rotor phase-b and stator phase-a is obtained?

Knowing the machine model expressed in an arbitrary **qd-reference** frame is

Stator side voltage equations:

$$\begin{bmatrix} u_{qs} \\ u_{ds} \\ u_{0s} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \cdot \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{0s} \end{bmatrix} + p \begin{bmatrix} \lambda_{qs} \\ \lambda_{ds} \\ \lambda_{0s} \end{bmatrix} - \omega_\theta \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \lambda_{qs} \\ \lambda_{ds} \\ \lambda_{0s} \end{bmatrix}$$

now d/dt

Rotor side voltage equations:

der er udført turns-ratio transformation

$$\begin{bmatrix} u'_{qr} \\ u'_{dr} \\ u'_{0r} \end{bmatrix} = \begin{bmatrix} R'_r & 0 & 0 \\ 0 & R'_r & 0 \\ 0 & 0 & R'_r \end{bmatrix} \cdot \begin{bmatrix} i'_{qr} \\ i'_{dr} \\ i'_{0r} \end{bmatrix} + p \begin{bmatrix} \lambda'_{qr} \\ \lambda'_{dr} \\ \lambda'_{0r} \end{bmatrix} - (\omega_\theta - \omega_r) \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \lambda'_{qr} \\ \lambda'_{dr} \\ \lambda'_{0r} \end{bmatrix}$$

(3) Suppose the rotor speed measured on the shaft is 240 rpm. The number of **pole pairs** of this induction machine is 4. Please calculate the value of rotor angular velocity ω_r, to be used in this machine model.

(4) Observed from Fig. 2 that when $\theta = 90$ degrees, the d-axis is aligned with stator phase-a axis and the q-axis is leading phase-a axis by 90 degrees. Let's fix this qd-frame at this position (let it become stationary). This makes the d-axis now become the alfa-axis and the q-axis is now the beta-axis. Please give the machine stator and rotor voltage equations expressed in this alfa, beta-reference frame. (*Please leave the zero component equations for simplicity.*)

$\omega t = 6$

Problem 4 **(25 %)**

The stator voltage equation of a permanent magnet synchronous machine may be given as (*same notations as used in the lecture slides*):

$$u_q = Ri_q + p\lambda_q + \omega_r \lambda_d \qquad \lambda_q = (L_{ls} + L_{mq}) i_q = L_q i_q$$

$$u_d = Ri_d + p\lambda_d - \omega_r \lambda_q \qquad \lambda_d = (L_{ls} + L_{md}) i_d + \lambda_{mpm} = L_d i_d + \lambda_{mpm}$$

(1) Please show the block diagram as you may implement in Simulink by using the d-axis voltage equation to solve for the d-axis current.

(2) If, at time t=0 in Simulink, you want the d-axis flux linkage λ_d to be equal to the rotor peak permanent magnet flux linkage λ_{mpm}, How can you achieve this in your Simulink model?

(3) In I/f control of the PM machine, should the current vector to be placed lagging the q-axis or should it be leading the q-axis? Please give your explanations.

(4) In steady state, you observe the phase-a voltage and current waveforms are as shown in Fig.4 (10 V for voltage and 2 A for current peak values). In addition, at the moment when phase-a voltage crosses the zero from negative to positive, the corresponding rotor position found is -30 electrical degrees. Please add the voltage space vector, the current space vector and the rotor dq-axes to Fig. 5, which should represent the instantaneous waveforms shown at t=0 in Fig. 4.

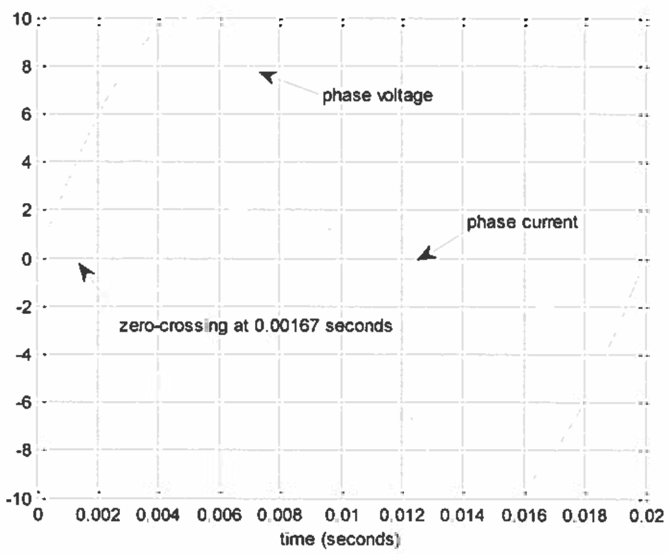

Fig. 4

Fig. 5

Written ~~examination in~~

Dynamic Models of Electrical Machines and Control Systems

1st semester M.Sc. (PED/EPSH/~~WPS/~~MCE)

Duration: 4 hours
(Reviewed by Dong Wang)

9.30 – 14.30

- All usual helping aids are allowed, including text books, slides, personal notes, and exercise solutions
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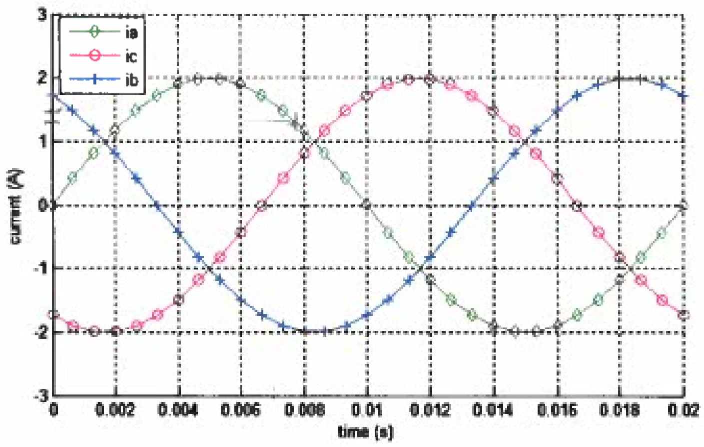
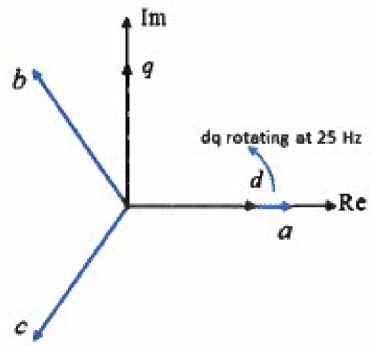
The set consists of 4 problems

Problem 1 (25%)

(1) Observe the following instantaneous a, b and c current waveforms (***Please pay attention to the phase sequence!***)



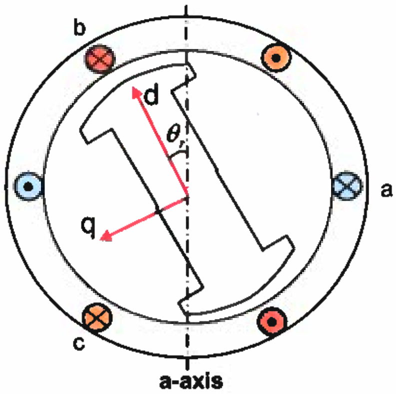


- Please indicate the rotating direction of the current space vector (clockwise or anti-clockwise)? Please explain.
- Please show the current space vector with respect to phase-a axis at time t = 0.0075 (seconds)
- Please draw the corresponding $\alpha\beta$ components for the time interval of [0.01, 0.02] seconds.
- A rotating dq reference frame is chosen. Its rotating frequency is at 100 Hz, anticlockwise direction. At t = 0, its d-axis is aligned with phase a-axis (as indicated above). Please draw the corresponding dq components for the time interval of [0, 0.02] seconds.

(2) Please find the space vector of the following a, b, c signals ($v_a = V_{pk}\cos(\omega_e t)$, $v_b = V_{pk}\cos\left(\omega_e t + \frac{2\pi}{3}\right)$, $v_c = V_{pk}\cos\left(\omega_e t - \frac{2\pi}{3}\right)$), using the same a, b, c-axes as shown in question (1).
Then, give the corresponding α and β components (viewed from a $\alpha\beta$ reference frame).

Problem 2 (25%)

A sketch of a synchronous machine is shown below.



(1) Please show how the mutual inductance between phase-a and phase-c may be derived.

(2) Please sketch this inductance vs. rotor position waveform (Y-axis: the above mutual inductance; X-axis: rotor position).

A simple single-phase PM machine is shown below in Fig. 2(a). Now another phase (naming it phase-b) is added to this machine, as indicated in Fig. 2(b).

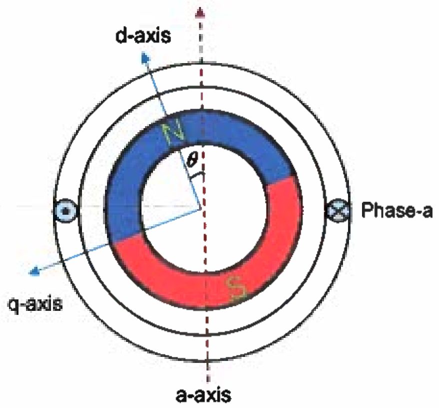


Fig. 2(a)

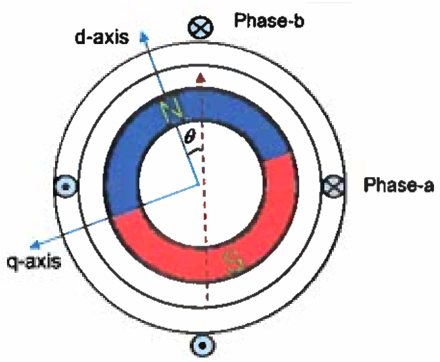


Fig. 2(b)

(3) If the phase-a PM flux linkage waveform is expressed as: $\lambda_{pm,a} = \lambda_{mpm} \cos\theta$. (where λ_{mpm} is its peak value and θ is the rotor position as indicated in Fig. 2), please give the PM flux linkage waveform for phase-b.

(4) If phase-a is now supplied with a current of $i_a = -I_m \sin\theta$ (where I_m is the peak value of the current), please determine the needed current waveform for phase-b, so that phase-b can produce the same torque profile as phase-a.

(5) Please show the instantaneous torque produced by phase-a and phase-b, respectively.

(6) Please give an expression for the total torque produced by phase-a and phase-b together.

930 - 10.45

Problem 3 (25 %)

An induction motor has the following data (**the rotor windings are short-circuited; the machine is Y-connected**):

Rated shaft power	7.5 kW
Rated speed	1160 rpm
Rated stator frequency	60 Hz
Number of poles	6
Rated stator voltage	380 V RMS (line-to-line)
Rated phase current	14 (A) RMS
Rated power factor cos φ	0.8 inductive
Stator resistance	0.28 Ohm

The stator side voltage equation may be expressed as

$$\begin{bmatrix} u_{qs} \\ u_{ds} \\ u_{0s} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \cdot \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{0s} \end{bmatrix} + p \begin{bmatrix} \lambda_{qs} \\ \lambda_{ds} \\ \lambda_{0s} \end{bmatrix} - \omega_\theta \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \lambda_{qs} \\ \lambda_{ds} \\ \lambda_{0s} \end{bmatrix}$$

(1) Please give the vector form of this voltage equation (taking q as the real component and d as the minus imaginary component, i.e. qd-reference frame).

(2) Please give the stator side voltage equation in a vector form expressed in the $\alpha\beta$-reference frame. Please calculate the magnitude of the stator flux linkage ($|\bar{\lambda}_{\alpha\beta s}|$) at the rated steady state operation condition.

(3) Now the motor is running at 0.1 Hz (electrical frequency) under V/f control. In order to maintain the same stator flux level as experienced at the rated condition, compensation of the voltage drop on the stator resistance needs to be introduced to the V/f control. In steady state, the phase-b current peak value is found to be 1.0 (A) and is lagging phase-b voltage by 30 degrees. Please determine the magnitude of the phase voltage vector after phase resistive voltage drop compensation.

(4) In V/f control, the stator frequency is now 50% of the rated frequency. The load torque is 25% of the rated torque. What is the slip frequency in Hz that needs to be compensated in order to make the **mechanical** rotor shaft speed to be 10 Hz?

1045 —

Problem 4 **(25 %)**

The stator voltage equation of a permanent magnet synchronous machine may be given as (*same notations as used in the lecture slides*):

$$u_q = Ri_q + p\lambda_q + \omega_r\lambda_d \qquad \lambda_q = (L_{ls} + L_{mq})i_q = L_q i_q$$

$$u_d = Ri_d + p\lambda_d - \omega_r\lambda_q \qquad \lambda_d = (L_{ls} + L_{md})i_d + \lambda_{mpm} = L_d i_d + \lambda_{mpm}$$

(1) This PM machine is driven by another DC motor and running at a constant speed of 1200 rpm. When the stator windings are open-circuited, measured line-to-line RMS voltage is 120 V. Please determine the value of λ_{mpm} to be used in the above machine equations; please also determine the corresponding d-, q-axes open-circuit voltages in dq0-reference frame.

(2) Please draw the block diagram indicating how you will implement the d-axis voltage and flux linkage equations in Simulink; what is the initial value to be set in the integrator in the implemented Simulink block diagram?

(3) For this PM machine, it is found that Ld > Lq, please sketch a possible location of the current vector with respect to the q-axis for achieving maximum torque per ampere operation.

(4) At a particular moment ($t = 0$), it is observed that the machine q-axis current is 3 (A) and its d-axis current is 1 (A) (in dq0 reference frame). At this moment, the rotor d-axis is leading the stator phase-a by 30 electrical degrees. The speed is constant and is 1200 rpm. Please draw stator phase-c current waveform for one period, starting from $t = 0$ as defined before. (Please indicate clearly *its initial current value at* $t = 0$ *and its peak value.)*

The power factor of this machine at this operation condition is 0.866 (voltage leading current). The phase rms voltage is 100 volts. Please add phase-c voltage waveform for one electrical period to the phase-c current waveform obtained previously.

Speed = 1200rpm

$I_{dq} = 1 + j3$