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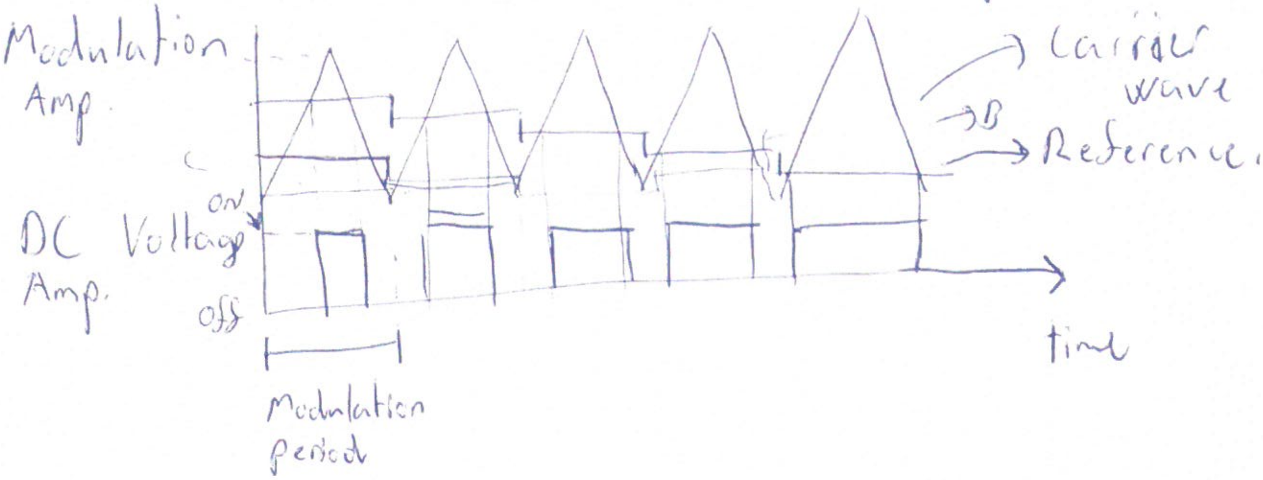
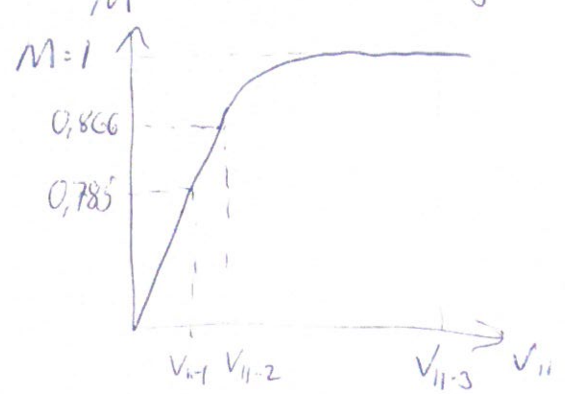
Part 1 - Modulation

- 3-Phase PWM
  - A reference is generated from a sine function and updated each cycle
  - This reference is compared with the triangular carrie wave
  - To generate a 3-phased signal, this the done 3- times where each sine function are 120° apart.



- Different ranges of Modulation



M. Modulation Index

V_{ll-1} - End of linear range for Sine-PWM

V_{ll-2} - End of linear range for SVM

V_{ll-3} - end of overmodulation.

$>V_{ll-3}$ - Square wave

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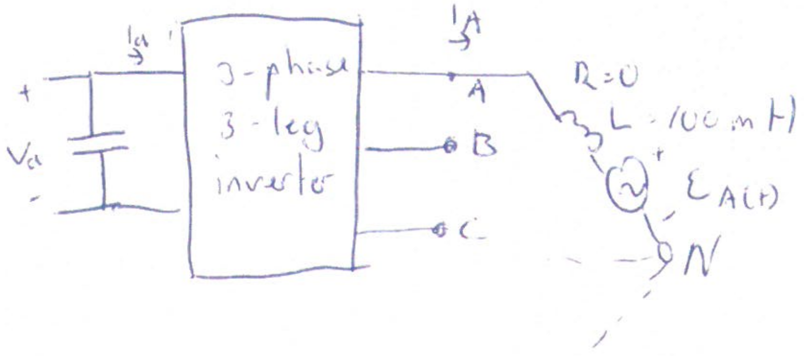
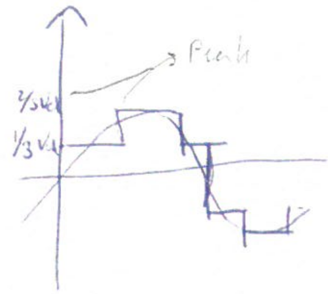
2 - A 3-phase Inverter works in square-wave mode

- $V_{LL} = 200V$, $f = 52\,Hz$





- Calculate the current ripple.

~~$V_d = \frac{\pi}{4}(\sqrt{2} \cdot V_{LL}) \quad V_{LL} = V_{LL}$~~
~~$= \frac{\pi}{4}(\sqrt{2} \cdot 200V) =$~~

$$V_{LL} = \frac{\sqrt{3}}{\sqrt{2}} \frac{4}{\pi} \frac{V_d}{2}$$
$\Downarrow$
$$V_d = 256,51V$$

$$w = 2\pi \cdot 52\,Hz = 326,7\,rad/s$$

$$\frac{T}{4} = \frac{1}{4} \cdot \frac{1}{52} = 4,8ms$$

~~$I_{ripple,peak} = \frac{1}{L} \int_0^{T/4} (V_d - 1/3 V_d - 2/3 V_d$~~

$$I_{ripple,peak} = \frac{1}{L} \int_{T/4}^{T/3} (2/3 V_d - (\overbrace{2/3 V_d}^{Peak} \cos(wt)))\,dt +$$
$$+ \frac{1}{L} \int_{T/3}^{T/2} (1/3 V_d - (\overbrace{2/3 V_d}^{Peak} \cos(wt)))\,dt = 10,7\,A$$

Origin Inductor

$$v_L = L \frac{di}{dt} \Rightarrow i = \frac{1}{L} \int v_L\,dt$$

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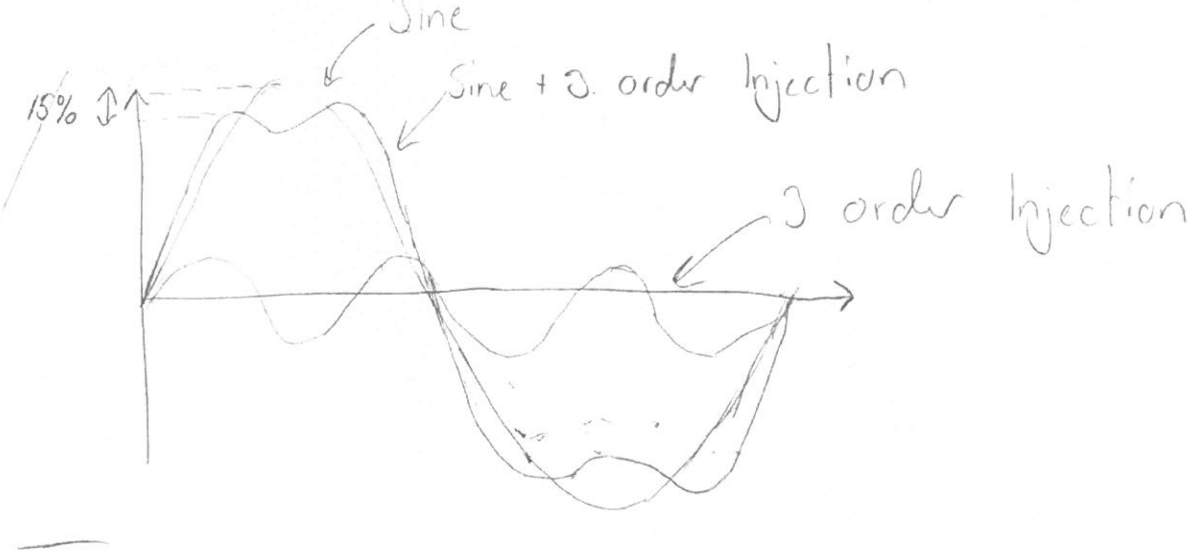
3- Increasing the linear range
The this is meant that the peak is reduced while maintaing the same area under the curve for the same period. Thereby, the DC Voltage can be used to a further extend (15%).

- The linear range cam be increase by
  - 3. order Injection
  - Space Vector Modulation



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1.4 - Electromagnetic Bracking

When the speed of the Motor is decreased, the kinetic energy stored in the motion is transformed back into electric energy.

↳ When the speed is decreased to the motor, the inertia will keep the rotor running effectively enabling generator mode.

- Dissipative mode → Brake Resistor
- Regerative braking → Four-Quadrant Inverter
  ↳ Energy supplied back to the grid.

1.5 - PWM-VSI / CSI

- Power Factor
  PWM better → CSI used on inductor where the motor is already inductive
  PWM uses a capacitor.
- Torque Pulsation
  PWM better → PWM has fast switchi
  ↳ Small V and I ripple
- Short Circuit protection
  CSI better → As the current is limited through the inducted
- Open Circuit protect:
  PWM better → As the capacitor doesn't react, but the CSI inductor realises large back EMF

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- Regenerative:
  PWM VSI - with four Quadrant Inverter.
  ↳ Good

  CSI has ~~a~~ large inductor, which can store a larger amount of energy than the capacitor

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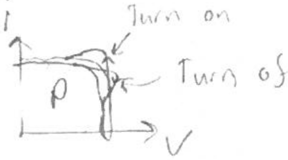
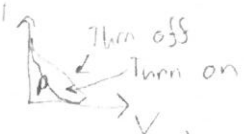
1.6 - Hard/Soft switching in case of power electronic converters?

- Hard switching:
  - Switches Directly



- Soft switching:
  - Used measures to reduce stress upon switching, and power



Thus hard switching has greater power loss than compared to soft switching

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Part 2

- A 4-pole surface mounted Permanent Magnet Machine is modeled in the qd-frame

$u_q = R i_q + p\lambda_q + w_r \lambda_d$ $\quad\quad$ $\lambda_q = (L_{ls} + L_{mq}) i_q$

$u_d = R i_d + p\lambda_d + w_r \lambda_q$ $\quad\quad$ $\lambda_d = (L_{ls} + L_{md}) i_d$

$T_e = 3/2\, p(\lambda_d i_q - \lambda_q i_d)$

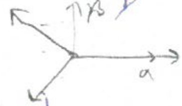
1 - Sketch the rotor structure:

2 - Indicate how rotor position is defined:
Angle between phase a and the d-axis.

- What current to a, b, c should be applied to force the rotor to its zero pos
  - Apply a constant/DC current through stator a to align the rotor with phase a, then $I_b = I_c = -I_a/2$
- What are $\alpha\beta$ commands to acchieve this:
As α is aligned with phase a

$u_\alpha = cst \rightarrow RI + \cancel{p\lambda_\alpha}^{0} + \cancel{w_r\lambda_\alpha}^{0}$

$u_\beta = 0 \rightarrow$



Since

$W_r = 0$, $\lambda_d = cst \rightarrow p\lambda_d = 0$

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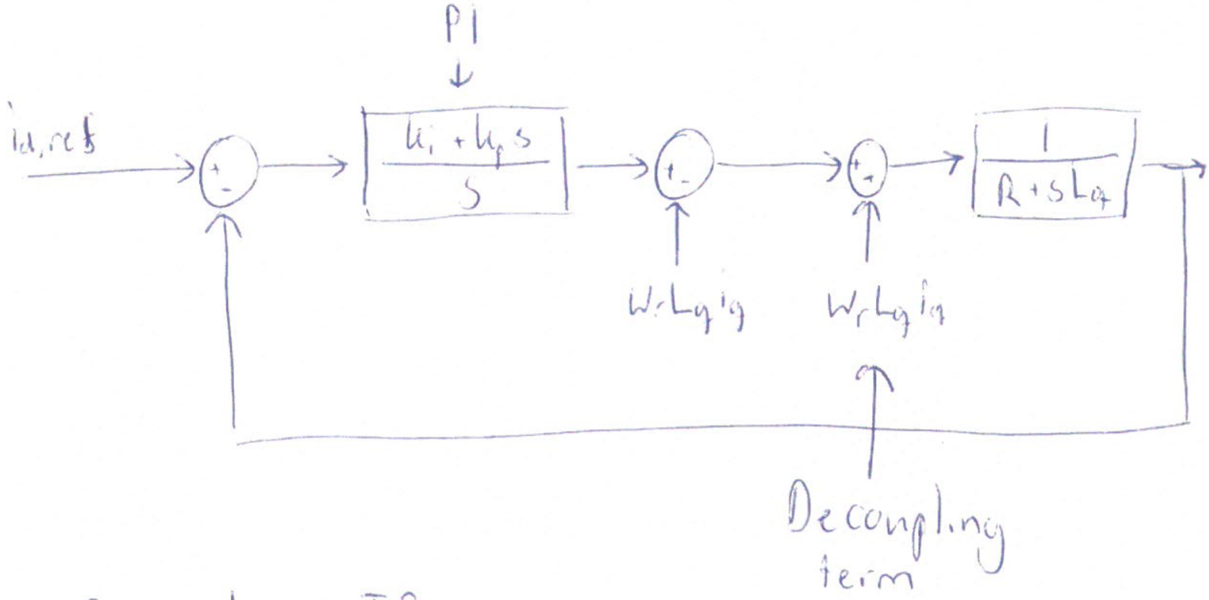
3 - The control Block Diagram for the d-axis current loop with the back-EMF decoupling term.



- Open-loop TF:

$$G(s) = \frac{k_i + k_p s}{s} \quad \frac{1}{R + sL_q}$$

$$\Rightarrow \frac{k_i + k_p s}{L_q s^2 + sR}$$

4 - Calculate the bandwidth of the q-axis current loop

- $R = 0{,}18$, $L_d = L_q = 2m$, $\lambda_{mpm} = 0{,}12$

  $k_p = 3$, $k_i = 100$

- If decoupled the loops for d and q are identical

$$G(s) = \frac{100 + 3s}{2m s^2 + s \cdot 0{,}18}$$

By inspection in MatLab the bandwidth is found to be:

$\omega_{bw} = 1650$ rad/s

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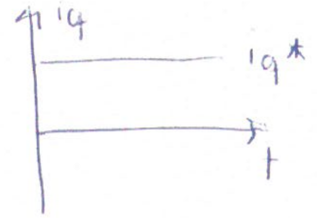
- The motor q-axis current response at zero speed for a step reference command (i_q^*) of:

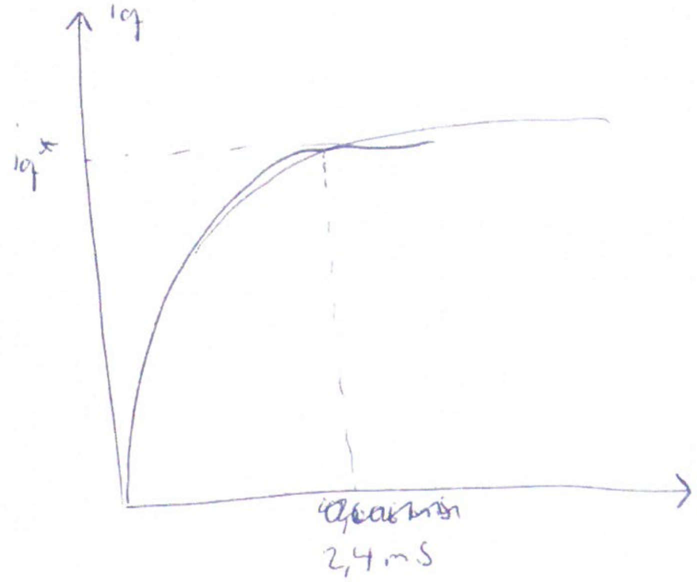


Since $w=0$ → ~~Perfect decoupling~~ No coupling.

$$G(s) = \frac{k_p}{L_q} \cdot \frac{s+k_i}{s} \cdot \frac{1}{s+R/L_q}$$

$$= \frac{3}{2m} \cdot \frac{s+100}{s} \cdot \frac{1}{s+0{,}18/2m} \Rightarrow \frac{3s+300}{2mS^2+0{,}98s}$$

Step:



Settling time

$T_s \approx \frac{4}{W_b}$ ← Bandwidth

Response:

Simple 1 order system

↳ ~~ABsie~~ $\simeq \frac{k}{s}$ → OL

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Part 3

- An induction Machine

1 - If $f_s = 50\,Hz$, calculate the speed of:

- Stator field:

  $\omega_s = 50 \cdot 2\pi = 314,15$ rad/s

- Rotor field

  $W_{r,el} = W_s - W_{se}$, $W_{se} = s\, W_s$

  so if $s = 0$ (no slip, i.e. no load)

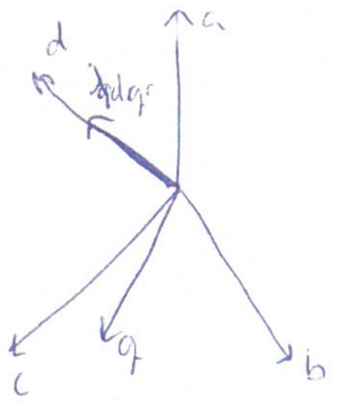
  $W_{r,el} = 314,15$ rad/s

- Air-gab field:

  ~~$W_{se} = W_s - W_{r,el}$ so if $s=0$ $W_{se} = 0$ rad/s~~ $W_{ag} = 50\,Hz \Rightarrow 314,15$ rad/s

2 - Rotor Flux Oriented Field Oriented Control

- Define the dq-reference frame



$\bar{\lambda}_{dqr} = \lambda_{dr} = \lambda_r$

so:

$\tau = \frac{3}{2} p \frac{L_m}{L_r} \mathrm{Im}(i_{dqs} \cdot \vec{\lambda}^*_{dqr})$

$= \frac{3}{2} p \frac{L_m}{L_r} (i_{qs}\, \lambda_r)$

The RFOFOC is oriented on the rotor flux vector $\Rightarrow$ dq-frame, hence d is aligned

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3 - In RFO FOC a step change is observed in the stator d-axis current

- Derive an equation linking rotor flux linkage to stator d-axis current:

As $\lambda_{qr} = 0$ and $\lambda_{dr} = \lambda_r$

From rotor side:

$$\lambda_{dr} = L_{lr} i_{dr} + L_m (i_{ds} + i_{dr}), \qquad L_{lr} + L_m = L_r$$

$$\lambda_r = L_r i_{dr} + L_m i_{ds}$$

and

$$0 = R_r i_{dr} + p \lambda_{dr}$$

Thus:

$$\left(1 + \frac{L_r}{R_r} p\right) \lambda_r = L_m i_{ds}$$

$\Downarrow$

$$\frac{\lambda_r}{i_{ds}} = \frac{L_m}{L_r/R_r\, s + 1}, \qquad \tau = \frac{L_r}{R_r}$$

- Derive an equation linking the rotor d-axis current to the stator d-axis current.

$$\left(1 + \frac{L_r}{R_r} p\right)\left(L_r i_{dr} + L_m i_{ds}\right) = L_m i_{ds}$$

$\Downarrow$

$$L_r i_{dr} + L_m i_{ds} + \frac{L_r}{R_r} p L_r i_{dr} + \frac{L_r}{R_r} p L_m i_{ds} = L_m i_{ds}$$

$\Downarrow$

$$L_r i_{dr} + \frac{L_r}{R_r} p L_r i_{dr} = L_m i_{ds} - L_m i_{ds} - \frac{L_r}{R_r} p L_m i_{ds}$$

$\Downarrow$

$$L_r \left(i_{dr} + \frac{1}{R_r} p L_r i_{dr}\right) = -\frac{L_r}{R_r} p L_m i_{ds}$$

$\Downarrow$

$$L_r i_{dr} \left(1 + \frac{1}{R_r} p L_r\right) = -\frac{L_r}{R_r} p L_m i_{ds}$$

$\Downarrow$

$$i_{dr} \left(1 + \frac{1}{R_r} p L_r\right) = -\frac{1}{R_r} p L_m i_{ds}$$

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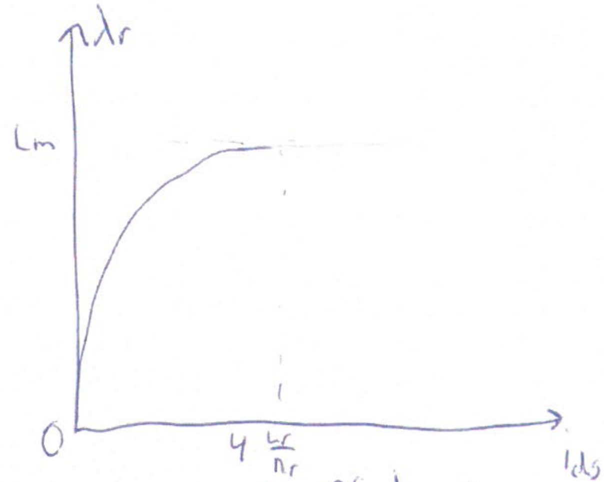
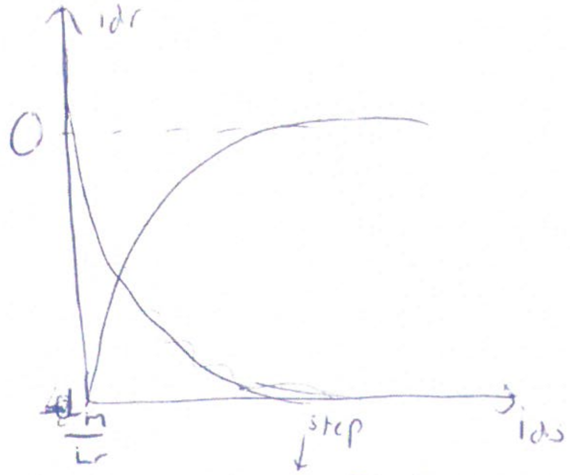
$$\frac{i_{dr}}{i_{ds}} = \frac{-\frac{1}{R_r} L_m s}{L_r/R_r \, s + 1} \quad , \quad \tau_r = \frac{L_r}{R_r}$$

Thus it yields a 1. order system with a free differentiator. i_{dr} starts high an dends to zero for a step ~~[illegible]~~.



$FV = \lim_{s\to 0} \frac{1}{s} s \cdot F(s) = L_m$

$IV = \lim_{s\to\infty} \frac{1}{s} s \; F(s) = 0$



$FV = \lim_{s\to 0} \frac{1}{s} s \, F(s) = 0$

$IV = \lim_{s\to\infty} \frac{1}{s} s \, F(s) = -\frac{L_m}{L_r}$