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Part 1

1 - PWM is a method in which a signal is switched between two state fast in order to approximate/generate an analogue signal.

↳ The signal "average" over time.

- PWM is needed in order to have digital processor generate an analogue signal.

2 - Modulation technique to decrease switching losses.

- Discontinuous PWM can be employed as it in theory reduce switching by 33%

↳ DPWM, the switches of one leg cease commutations for 1/3 of the fundamental period

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a) - The major disadvantage with e.g wind/PV
The main disadvantage is the energy production profile
↳ It fluctuates.

- Solution
  - Back-to-back Converter Topology
    ↳ Seperate the variable frequency of the turbine from the fixed frequency of the grid.
  - Storage System
    ↳ The grid can be supported by charging and discharging the storage system according to the grid
    ↳ If the production is too high, the active power can be stored and thus limiting the power production is not necessary.

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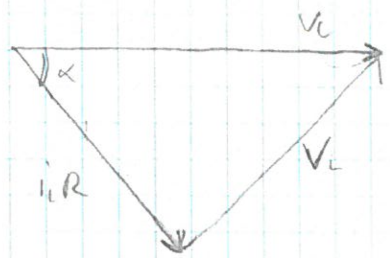
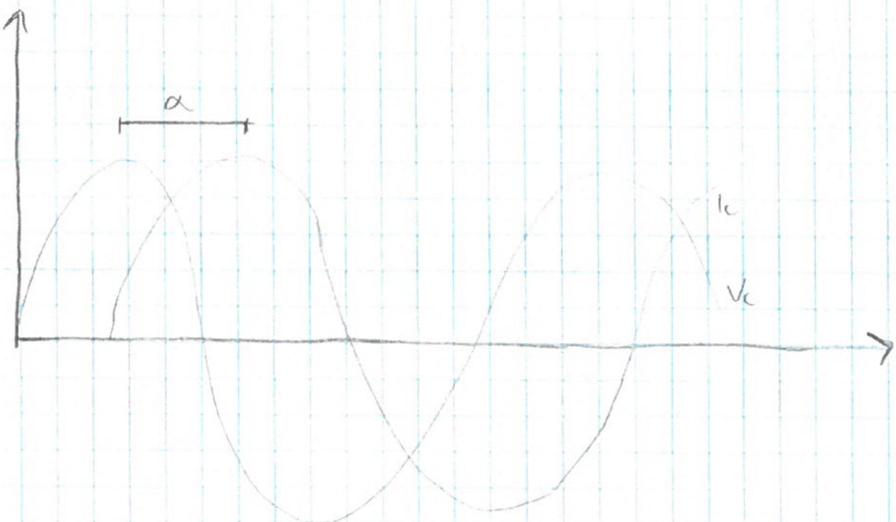
4 - RL - load



V_c : Converter Voltage
I_c : Converter Current
I_R : Resistive Current
I_L : Inductive Current.



5 - Range of an electric car
If the battery pack size is fixed, the range of the car can be increased by electromagnetic braking, which during braking uses the additional energy to charge the battery.

- Other measure
  - Reducing Switching Losses
    ↳ DPWM.

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6 - Square Wave modulated converter / PWM converter

- Power Factor
  PWM performs better, since SW has thyristors, which introduce additional reactive power
  Furtermore, PWM switches fast, enabling fast response to a change in PF, whereas SW's thyristor can't be turned off when desired.

- Torque Pulsation
  PWM → Fast switching
  ↳ Small V & I ripples
  SW → Slow switching
  ↳ Larger V & I ripples
  ↳ $T \propto I$

- Efficiency at low speed
  PWM → Fast switching
  ↳ f_n / f_{switch} → Lower
  SW → Slow Switching
  ↳ f_n / f_{swich} → Higher
  ↳ Less switching losses

- Ride Through Capability
  PWM → Fast Control, can response to a brief drop in grid side voltage

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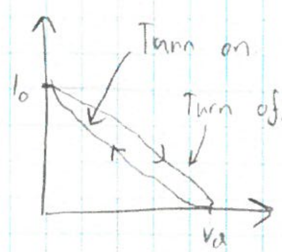
SW → Cannot respond as fast.

- Short Circuit protection:
  Both PWM and SW has poor SC-protection, since there is nothing to limit the current
  ↳ Short the DC-link Capacitor

7 - Soft switching:
Soft switching is a method in which the rate the transistor switches at is limited
- It can be achieved through varies methods:
  - Snubber Circuit
  - Resonance Tank

- Example on Soft switching Trajectory:



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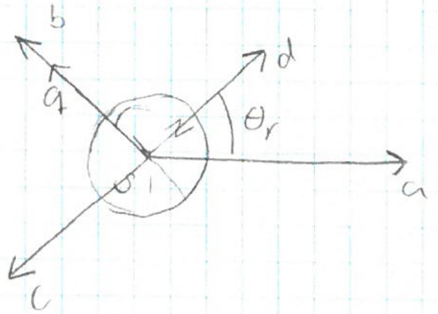
Part 2 PMSM

A 8-pole surface mounted PMSM in synchronous reference frame.

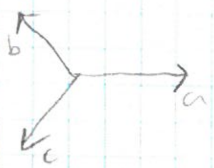
1 - Rotor dq-reference frame



2 - $\theta_r = 0$, Rotor alignment

$\theta_r = 0 \rightarrow$ Rotor is aligned

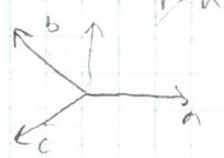
- Apply a constant/DC current through stator phase a
  - $i_b = i_c = i_a/2$



- In $\alpha\beta$
  - As α is aligned with phase a:

$u_\alpha = cst \rightarrow RI + \cancelto{0}{p\lambda_\alpha} + \cancelto{0}{\omega_r \lambda_\beta}$

$u_\beta = 0$



$u_b = u_c = 0 \cdot u_\beta$

Since

$\omega_r = 0, \quad \lambda_\alpha = cst \rightarrow \underbrace{p\lambda_\alpha = 0}_{\text{Steady State}}$

$i_\alpha = i_a$

$i_\beta = 0$

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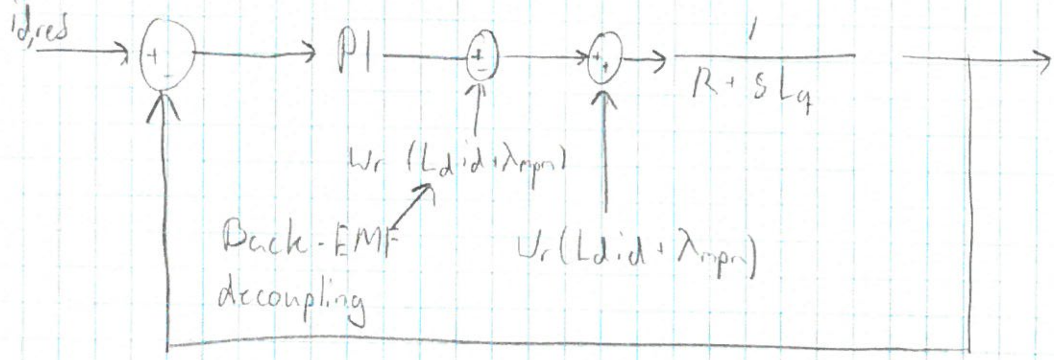
3 - Shaft speed at 1200 rpm
- Value of w_r to be used in the machine eqs.

$$w_{r,el} = p \cdot w_{r,shaft}$$

$$w_{r,el} = 4 \cdot 1200 \text{ rpm} = 4800 \text{ rpm} \Rightarrow 502{,}7 \text{ rad/s}$$

4 - Control

- Control the q-axis current to follow a reference current command



- Transfer function

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

$$= \frac{k_p}{L_q} \frac{s + k_i/k_p}{s^2 + \frac{R}{L_q} s}$$

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5. Step

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

$k_p = 3$, $k_i = 100$

- Bandwidth

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

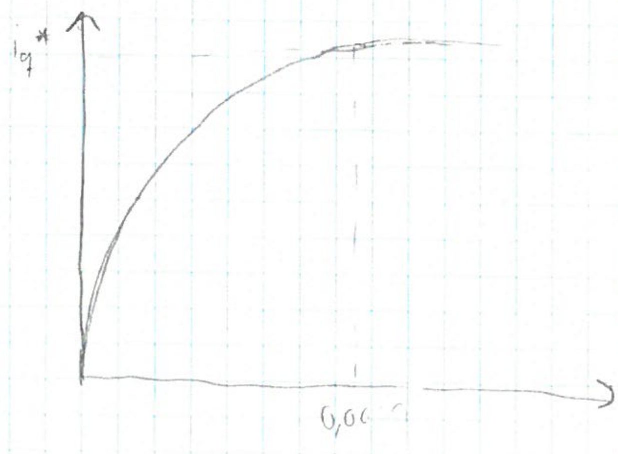
$$= 1500 \cdot \frac{s + 33{,}3}{s^2 + 90s}$$

In frequency domain:

$$\left| 1500 \cdot \frac{j\omega + 33{,}3}{j\omega^2 + 90j\omega} \right| = -3dB$$

$\omega_{bw} = 2090$ rad/s

- Step



For PI

$T_s = \frac{4}{\omega_{bw}} = 0{,}0019$

For System.

$\omega_{bw} = 1460$

$T_s = \frac{4}{\omega_{bw}} =$

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Part 3 - IM

1 - Torque

$$\tau = \frac{3}{2} p \frac{L_m}{L_r} \operatorname{Im}\left(i_{qds} \cdot \lambda_{qdr}^*\right)$$

$\Downarrow$ $\bar{\lambda}_{dqr} = \lambda_{dr} = \lambda_r$ → since d is aligned with $\bar{\lambda}_{dqr}$

$$\tau = \frac{3}{2} p \frac{L_m}{L_r} \operatorname{Im}\left(i_{ds} + j i_{qs}\right)\left(\lambda_{dr} + j \lambda_{qr}\right)$$

$\Downarrow$

$$\tau = \frac{3}{2} p \frac{L_m}{L_r} \left(i_{qs} \lambda_{dr} + i_{ds} \lambda_{qr}\right)$$

$\Downarrow$ since $\lambda_{qr} = 0$

$$\tau = \frac{3}{2} p \frac{L_m}{L_r} \left(i_{qs} \lambda_{dr}\right)$$

2 - Machine eqs. in rotor flux oriented

- Stator Side

$u_{qs} = r_s i_{qs} + p \lambda_{qs} + \omega_e \lambda_{ds}$ $\qquad \lambda_{qs} = L_{ls} i_{qs} + L_m (i_{qs} + i_{q}$

$u_{ds} = r_s i_{ds} + p \lambda_{ds} + \omega_e \lambda_{qs}$ $\qquad \lambda_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr})$

Unchanged!

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- Rotor Side:

$u_{qr} = r_r i_{qr} + p\lambda_{qr} + (\omega_e - \omega_r)\lambda_{dr}$ $\lambda_{qr} = L_{lr} i_{qr} + L_m(i_{qs} + i_{qr})$

$u_{dr} = r_r i_{dr} + p\lambda_{dr} - (\omega_e - \omega_r)\lambda_{qr}$ $\lambda_{dr} = L_{lr} i_{dr} + L_m(i_{ds} + i_{dr})$

$\Downarrow$ Since $u_r = 0$, $\lambda_{qr} = 0$, $\lambda_{dr} = \lambda_r$

$0 = r_r i_{qr} + (\omega_e - \omega_r)\lambda_r$ $0 = L_r i_{qr} + L_m i_{qs}$

$0 = r_r i_{dr} + p\lambda_r$ $\lambda_r = L_r i_{dr} + L_m i_{ds}$

Estimation of slip:

- From q-axis

$0 = L_r i_{qr} + L_m i_{qs}$

$\Downarrow$

$i_{qr} = -\frac{L_m}{L_r} i_{qs}$

Substitute into u_{qr}:

$s\omega_e = r_r \frac{L_m}{L_r} \frac{i_{qs}}{\lambda_r}$

Estimation of rotor flux:

- From d-axis

$\begin{cases} 0 = r_r i_{dr} + p\lambda_{dr} \\ \text{and} \\ \lambda_r = L_r i_{dr} + L_m i_{ds} \end{cases}$

$\Downarrow$

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

$\Downarrow$

$\lambda_r = \frac{L_m}{1 + p\frac{L_r}{r_r} p} i_{ds}$

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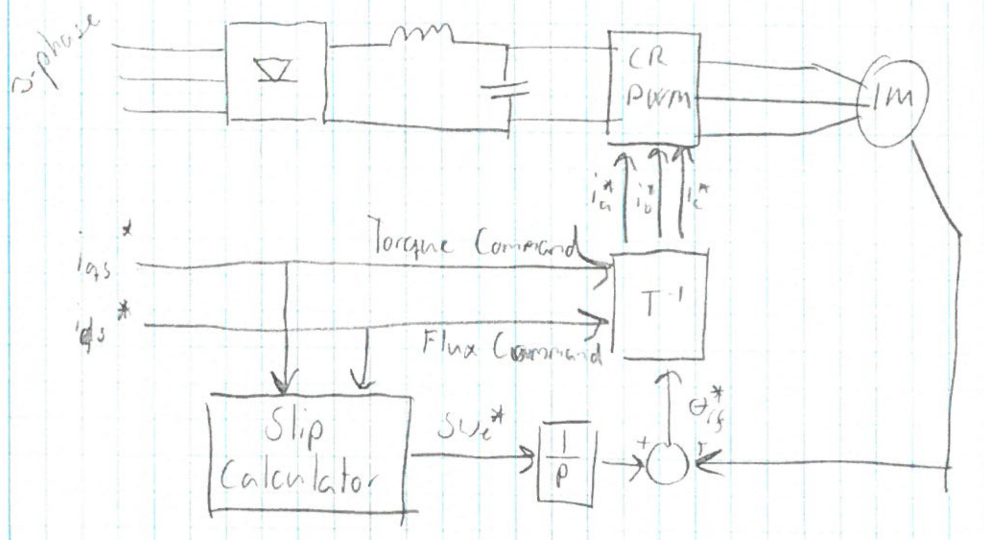
3.- Vector Controller



- A step change is applied to the d-axis current command.
  ↳ How does i_{dr} react?
  By inserting the for the rotor flux into that of the rotor voltage, it yields:

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

$$\Downarrow$$

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

Hence the rotor current response with a first order system with a time constant of L_r/R_r and an

$$\begin{cases} FV = 0 \\ IV = -L_m/L_r \end{cases}$$

⇓
Decays to zero

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- A step change is applied to the q-axis current command
  ↳ How does i_{qr} react?

By evaluating

$$i_{qr} = -\frac{L_m}{L_r} i_{qs}$$

Thus the current reacts instantaniously.