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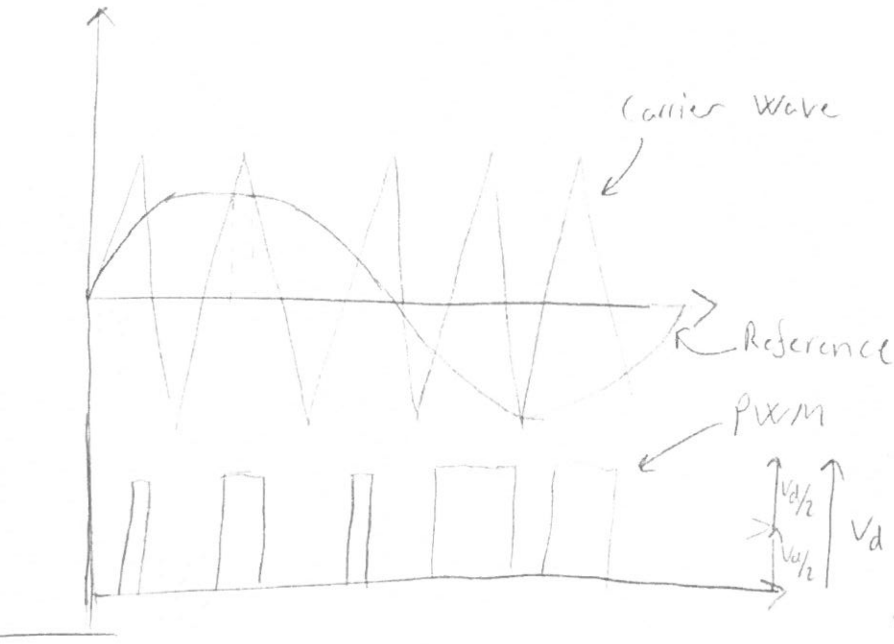
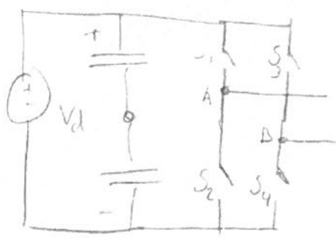
Part 1 - Modulation

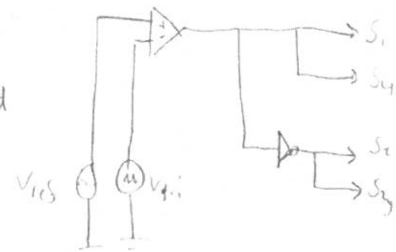
1 - Single-phase analogue PWM technique
- A reference signal is generated and compared with a triangular carrier wave.



H-Bridge



Bipolar PWM

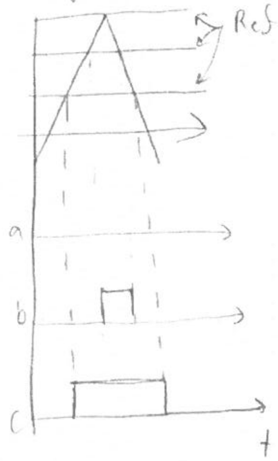


2 - Discontinuous PWM (DPWM)

DPWM allows reducing the average switching, which is particular suitable for high-power inverters.

Considering similar switching frequency (same carrier frequency), DPWM gives a 1/3 reduction of the average switching frequency, thus reducing switching losses by 33%.

- Implementation DPWM:



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3- An electric drive switches from motor to generator

- What happens with the DC-link
  - Energy will build up in the capacitor, if no precaution is taken and the capacitor limit are exceeded, this will damage the inverter
- Reason
  - This is caused by the fact that the motor is operating in generator mode.

4. - Limit the phenomena of 1.3
   - Dissipative braking
     - ↳ A resistor is set in parallel with the DC-link capacitor to dissipate the energy.
   - Regenerative braking
     ↳ A 4-Quadrant inverter is used to deliver energy back to the grid.

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5. Comparison of Adjustable Frequency Drives

	PWM	Square Wave	CSI
Power factor S.p. 5/21 L4	Uses a capacitor, thus a smaller PF angle. (✓) - Faster control	Uses a capacitor, thus a smaller PF angle. (✓) - Thyristor causes reactive P ↳ Don't swicht when wanted	Uses a inductor, (✓) where the motor already is inductive
Torque Pulsation	Fast switching → Small V & I ripples. ✓	Slow switching → Larger V & I ripples $\tau \propto I$ ✓	Thyristor can only be turned off, when I = 0, i.e. only once per fundamental.
Regeneration	Needs a Four Quadrant inverter is supplyed by grid. ✓		Has a large inductor, which can store a larger amount of energy then the DC-link capacitor ✓
Short circuit protection	Shorts the DC-link (✓)		The current is limited by the inductor (✓)
Open Circuit protection	Current stops flowing ↳ No consequence ✓		Overvoltage, caused by the energy stored in the inductor. ✓ - Current can't change instantanions
Size and weigth	Physically smaller than CSI (✓)		Large Inductor (✓)
Multi Motor Capability	Voltage distributed equally across multible motors Same voltage on each		Current depends on the load, Current divides.
Ride-through capability	Fast Control, can response to a ms drop in voltage ✓	Slow Switching cannot response ✓	Slow response ↳ The large L can compensate for ✓

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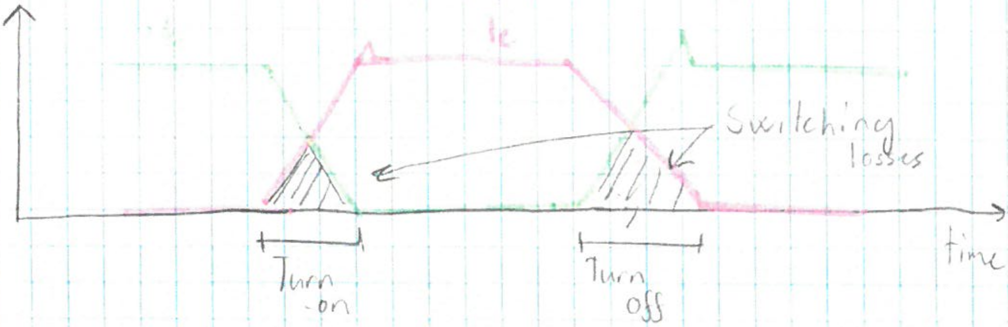
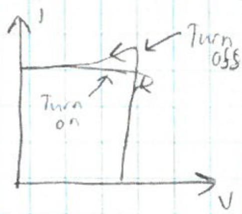
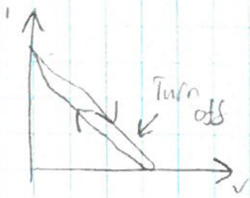
1.6 - MosFET / IGBT turn on/off



- During turn on/off periods, switching losses appears.
- Since the switches are not ideal, the switching does not happen instantanious.

- The switching trajectory





Hard switching   Soft switching.

So by soft switching the switching trajectory is increased.
↳ This can by achieved by adding a snubber capacitor or a resonance tank.

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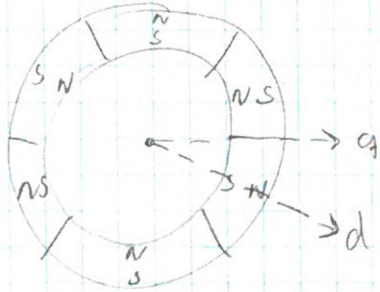
Part 2 - PMSM

A 6-pole surface Mounted PMSM

2.1 - dq-reference frame



q leads d with 90° electrical

→ 90°/3 ← pole pairs

2.2 - Torque eq.

- Torque expressed by dq inductances and currents

$$T_e = \frac{3}{2} p \left(\lambda_{mpm} i_q + (L_d - L_q) i_d i_q \right)$$

⇓ Since Surface Mounted, $L_d = L_q$

$$T_e = \frac{3}{2} p \left(\lambda_{mpm} i_q \right)$$

- Determination of d and q-axis current references for FOC:

$i_{d,ref} = 0$

$i_{q,ref}$ can be found either by $K(\omega_{ref} - \omega) \cdot PI$ - Through a speed loop or through a torque reference:

$$i^*_{q,ref} = \frac{2}{3} \frac{T^*_{e,ref}}{p \lambda_{mpm}}$$

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2.3 - The machine shaft speed

$w_r = 377$ rad/s

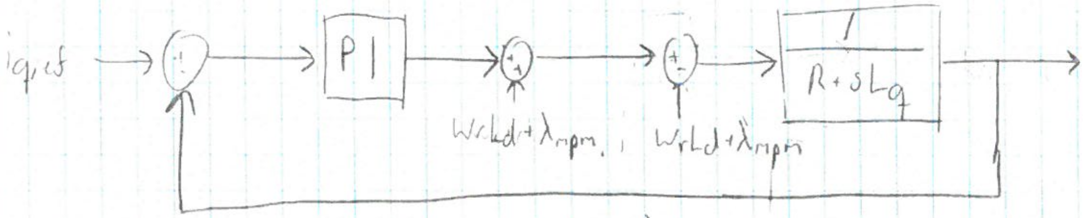
$w_{r,shaft} = w_r / p$

$w_{r,shaft} = \frac{377 \text{ rad/s}}{3} \cdot \frac{60}{2\pi} = 1200 \text{rpm}$

2.4 - Tune the current loop PI parameters at zero speed (Recommended):

- At "zero" speed there is no coupling i.e. the back EMF is zero.

2.5 - Control block Diagram for the q-axis



Since $u_q = R i_d + p\lambda_d + w_r^{0} (L_d i_d + \lambda_{mpm})$. ← No coupling.

Open Loop Transfer Function:

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

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

$$= \frac{1}{L_q} \frac{k_p s + k_i}{s^2 + \frac{R}{L_q} s}$$

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

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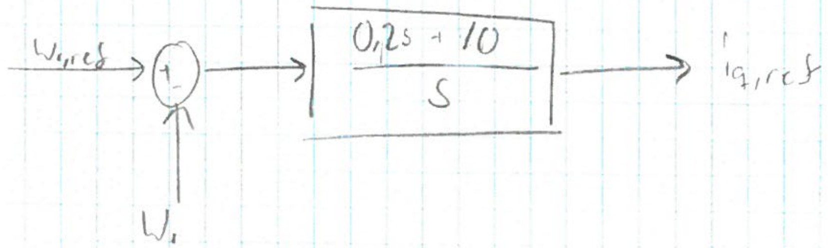
2.6 - Step

The motor is running at 1000 rpm

- $k_p = 0,2$, $k_i = 10$

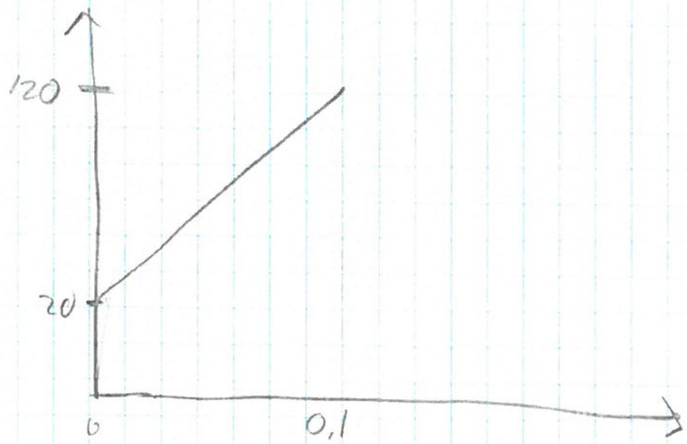
A new speed reference of 1100 rpm is introduced:

- The change in q-current reference command for the next 0,1 s:



$i_{q,ref,init} = (1100 - 1000) \cdot 0,2 = 20\,A$, at $t = 0$

$i_{q,ref,final} = (1100 - 1000) \cdot 0,2 + 10 \cdot \int_0^{0,1} 100 \, dt = 120\,A$, at $t = 0,1$



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Part 3 - Induction Motor

1 - Rotational Speed

$f_{supply} = 50\,Hz$

- Rotor field

$w_{r,el} = w_s - w_{sc}$, $w_{sc} = s \cdot w_s$

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

$w_{r,el} = 50 \cdot 2\pi = 314,15\ rad/s$

- Stator field:

$w_s = f_s \cdot 2\pi$

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

- Air gab field:

$w_{sc} = w_s - w_{r,el}$

so if $s = 0$

$w_{sc} = 0\ rad/s$.

2 - Rotor Flux Oriented Field Oriented Control

- Torque eq

$$\tau = \frac{3}{2} p \frac{L_m}{L_r} \operatorname{Im}\left(\bar{i}_{qds} \cdot \bar{\lambda}_{qdr}\right),$$

since $\bar{\lambda}_{qdr} = \lambda_{dr} = \lambda_r$

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

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3 - RFO FOC

- Derive an expression linking rotor flux magnitude and stator d-axis current:

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

From rotor side:

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

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

and

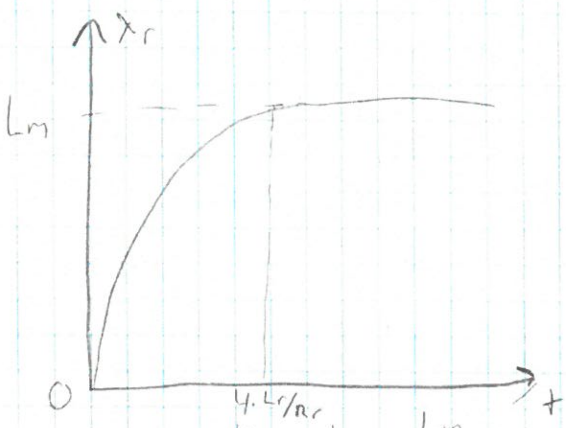
$$0 = R_r i_{dr} + p \lambda_{dr}$$

Thus

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

$$\Downarrow \quad \frac{\lambda_r}{i_{ds}} = \frac{L_m}{{}^{L_r}/_{R_r} s + 1}, \qquad \tau_r = \frac{L_r}{R_r}$$

- Step



$$FV = \lim_{s \to 0} \frac{1}{s} \cdot s \frac{L_m}{{}^{L_r}/_{R_r} s + 1} = L_m$$

$$IV = \lim_{s \to \infty} \frac{1}{s} \cdot s \frac{L_m}{{}^{L_r}/_{R_r} \cdot s + 1} = 0$$

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4 - Types of FOC:

- Rotor - flux oriented FOC is the simplest

- Motor Parameters needed
  - R_r, R_s, L_{ls}, L_{lr}, L_m, p k_{er}, ratio:
  Lecture 1, slide 14