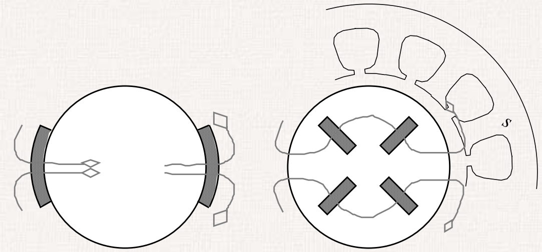
PMSM

Industrial Electrical Engineering and Automation
Lund University, Sweden

Mechanical Design

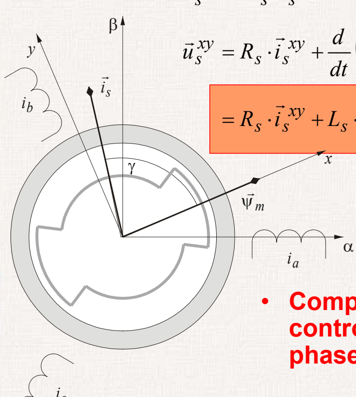


Mathematical Model

$$\vec{u}_s^{\alpha\beta} = R_s \cdot \vec{i}_s^{\alpha\beta} + \frac{d\vec{\psi}_s^{\alpha\beta}}{dt} = R_s \cdot \vec{i}_s^{\alpha\beta} + \frac{d}{dt}\left(\vec{\psi}_m^{\alpha\beta} + L_s \cdot \vec{i}_s^{\alpha\beta}\right)$$

$$\vec{u}_s^{xy} = R_s \cdot \vec{i}_s^{xy} + \frac{d}{dt}\left(\vec{\psi}_m^{xy} + L_s \cdot \vec{i}_s^{xy}\right) + j\omega_r \cdot \left(\vec{\psi}_m^{xy} + L_s \cdot \vec{i}_s^{xy}\right)$$

$$= R_s \cdot \vec{i}_s^{xy} + L_s \cdot \frac{d\vec{i}_s^{xy}}{dt} + j\omega_r \cdot \left(\vec{\psi}_m^{xy} + L_s \cdot \vec{i}_s^{xy}\right)$$



- Compare to the vector control of a generic 3-phase load...

Torque Control

$$T = \vec{\psi}_s \times \vec{i}_s = \psi_{sx} \cdot i_{sy} - \psi_{sy} \cdot i_{sx} =$$

$$= \left(\psi_m + L_{sx} \cdot i_{sx}\right) \cdot i_{sy} - L_{sy} \cdot i_{sy} \cdot i_{sx} =$$

$$= \psi_m \cdot i_{sy} + \left(L_{sx} - L_{sy}\right) \cdot i_{sx} \cdot i_{sy}$$

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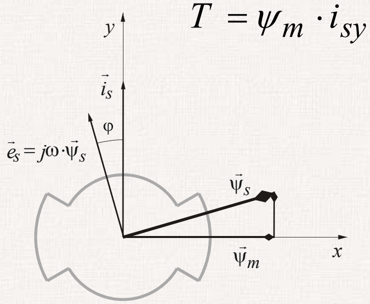
Simplest, only y-axis current control

$$T = \psi_m \cdot i_{sy}$$

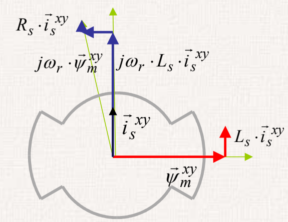


$$\begin{cases} i_{sx}^* = 0 \\ i_{sy}^* = \dfrac{T^*}{\psi_m} \end{cases}$$

Drawback with y-axis control

- Does not utilize the reluctance torque
- Phase lag between voltage and current

$$\vec{u}_s^{xy} = R_s \cdot \vec{i}_s^{xy} + L_s \cdot \frac{d\vec{i}_s^{xy}}{dt} + j\omega_r \cdot \left(\vec{\psi}_m^{xy} + L_s \cdot \vec{i}_s^{xy}\right)$$

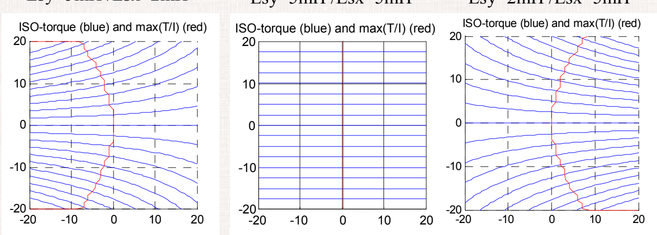


Better – max Torque/Ampére control

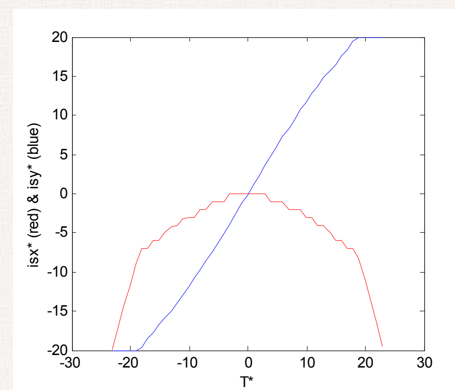
- Orient the current vector for maximum Torque.

$$T = \psi_m \cdot i_{sy} + (L_{sx} - L_{sy}) \cdot i_{sx} \cdot i_{sy} =$$
$$= \psi_m \cdot i_s \cdot \cos(\delta) + (L_{sx} - L_{sy}) \cdot i_s^2 \cdot \cos(\delta) \cdot \sin(\delta)$$

Lsy=5mH /Lsx=2mH　　Lsy=5mH /Lsx=5mH　　Lsy=2mH /Lsx=5mH



Look up table for current setpoints



Voltage limitation

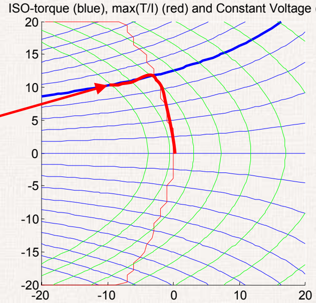
- When the machine speeds up, a voltage limit is reached.
- The speed can be further increased with the help of ”field weakening”

Voltage limitation

$$|\vec{u}_s| = \sqrt{\left(R_s \cdot i_{sx} - \omega_r \cdot L_{sy} \cdot i_{sy}\right)^2 + \left(R_s \cdot i_{sy} + \omega_r \cdot \left(\psi_m + L_{sx} \cdot i_{sx}\right)\right)^2}$$

- What current combinations satisfy a limited voltage vector?

Follow $(T/I)_{max}$ to Voltage limit, then T=const.



Example: an EV traction motor

A-sample Characteristics

Interior Permanent Magnet Motor

Field Weakening

Water Cooled

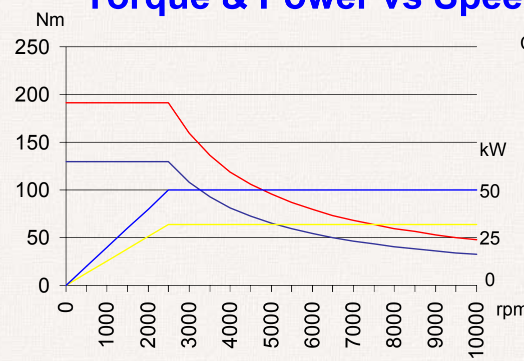
Position Feedback with resolver

Drive Unit Specifications

- Max power 50 kW (2 min)
- Continuous power 32 kW
- Max torque 191 Nm (2 min)
- Continuous torque 130 Nm
- Efficiency range ~ 85 - 95 %
- Nominal DC-link voltage: 200 - 320 V (braking 240 - 350 V)
- Base speed 2500 rpm
- Speed range 0 - 10000 rpm
- Max cooling liquid temp 70 °C

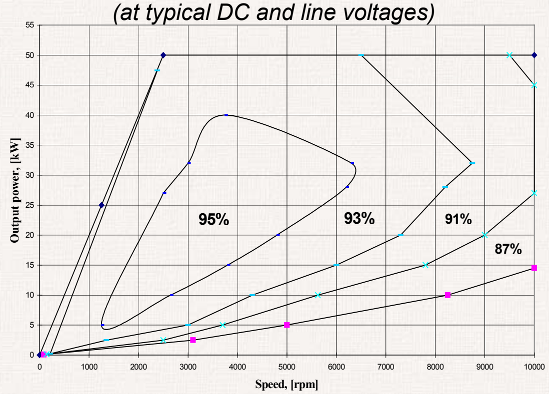
Length	Motor	250 mm
	Converter	392 mm
Width	Motor (dia)	260 mm
	Converter	260 mm
Height	Motor (dia)	260 mm
	Converter	80/128 mm
	System	340 mm
Weight	Ca 60 kg	

Torque & Power vs Speed



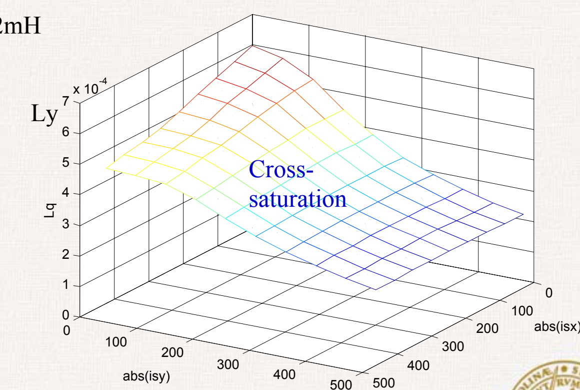
Efficiency Curves 50 kW motor

(at typical DC and line voltages)

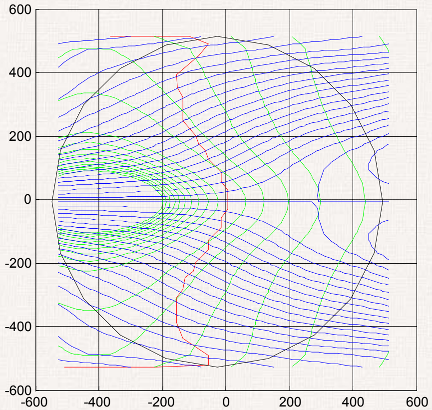


Magnetic saturation (Ly)

Lx=0.2mH



Torque control



How to realize field weakening?

1. Look up table of i_{sx} as a function of speed
2. Estimate induced voltage
   – @ to high e_y, adjust i_{sx} until e_y is below limit

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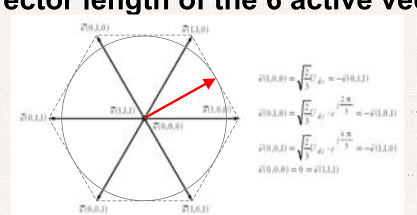
What is the maximum voltage vector?

- Vector length of the 6 active vectors:



- Largest ensribed circle

$$\sqrt{\frac{2}{3}}U_{dc}\cdot\cos(30°)=\sqrt{\frac{2}{3}}U_{dc}\cdot\frac{\sqrt{3}}{2}=\frac{U_{dc}}{\sqrt{2}}$$

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Use slightly lower limit

- 20 % below, e.g. With a 250 V DC-link voltage, the highest allowed vector should be:

$$|\vec{u}|_{\max}=\frac{250}{\sqrt{2}}=177$$

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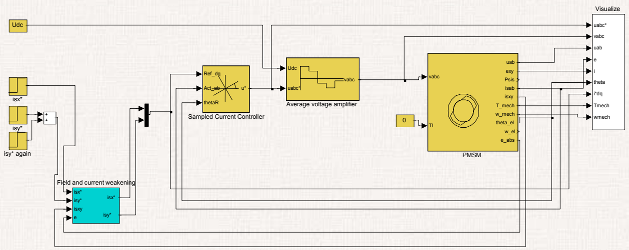
Simulation example



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End of PMSM story

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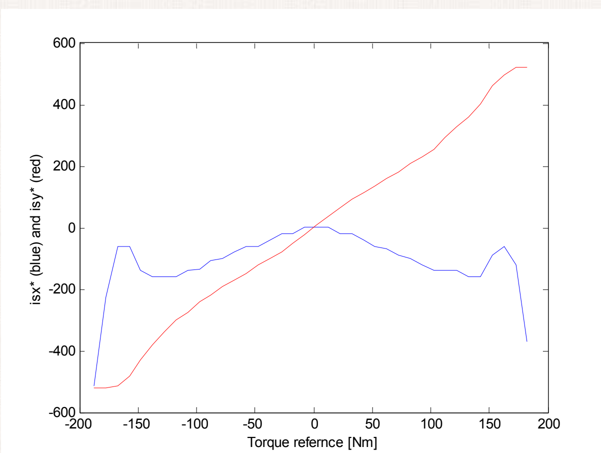
Current references



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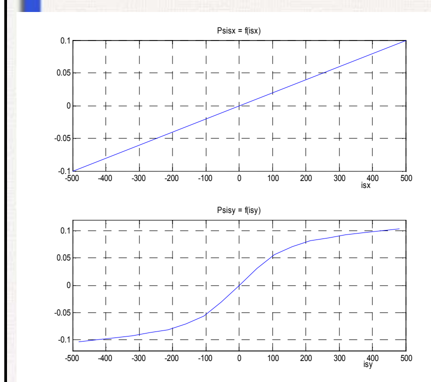
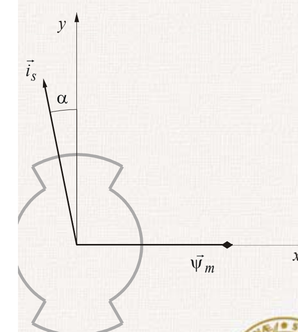
Minimum stator current control





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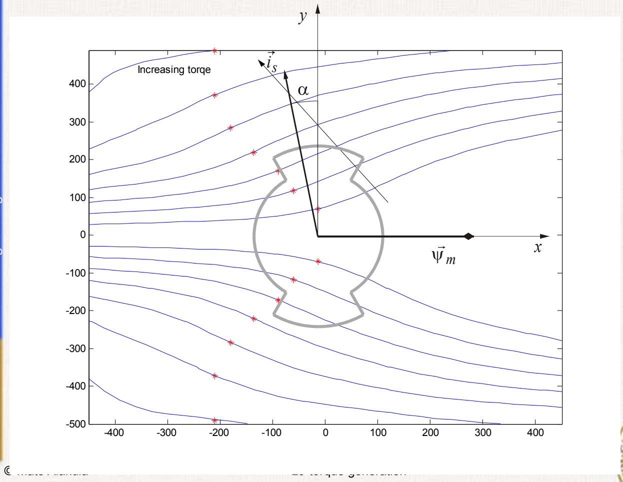
”Iso”-torque curves



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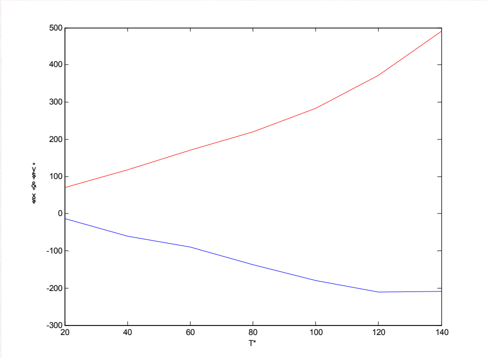
Look up tables for minimal stator currents



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Simulation 2

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Field Weakening

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Field Weakening

$$|\vec{u}_s| = \sqrt{\left(R_s \cdot i_{sx} - \omega_r \cdot L_{sy}(i_{sx}, i_{sy}) \cdot i_{sy}\right)^2 + \left(R_s \cdot i_{sy} - \omega_r \cdot \left(\psi_m + L_{sx}(i_{sx}, i_{sy}) \cdot i_{sx}\right)\right)^2}$$

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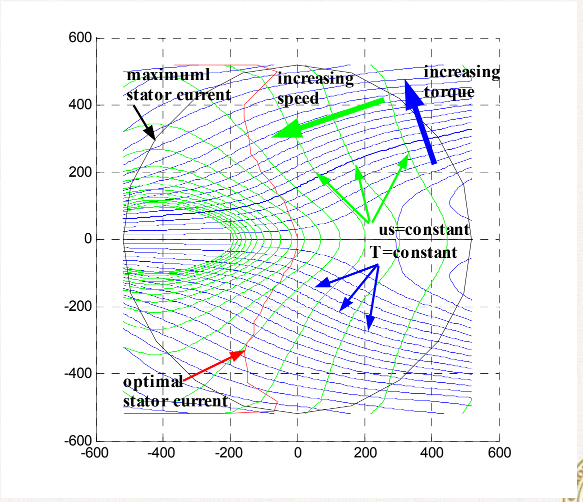

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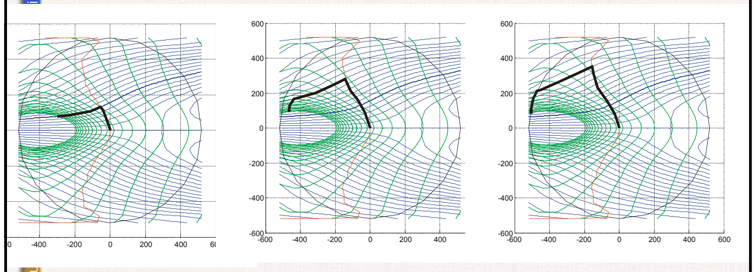
Priorit y	Action
1	Stator current less than maximum stator current (Current limitation to protect machine and power electronics)
2	Stator voltage less than maximum stator voltage (Voltage limitation to facilitate current control)
3	Minimal stator current for a given torque (Stator current on the optimal line)



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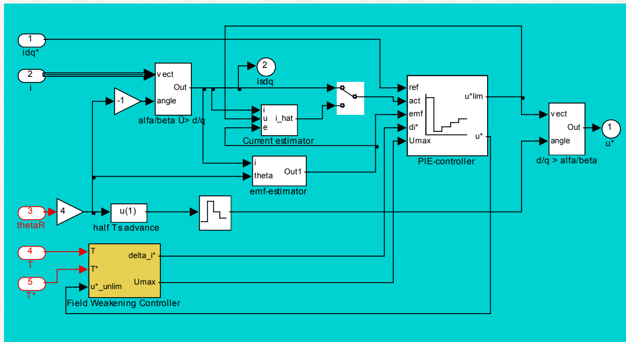

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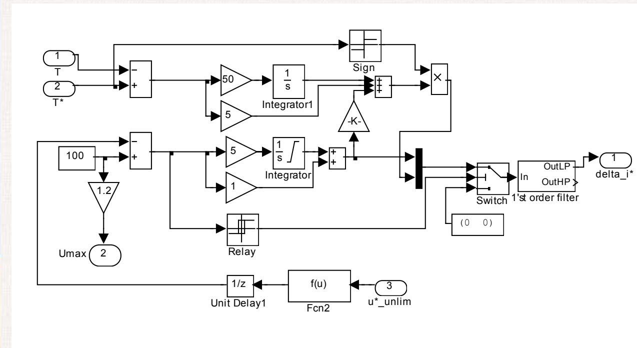

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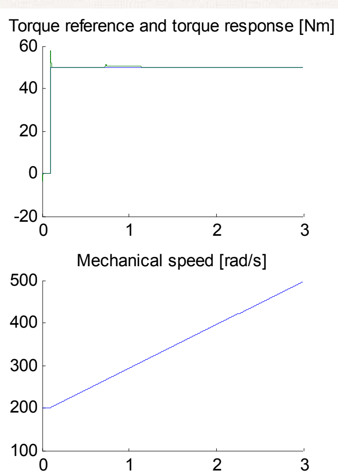

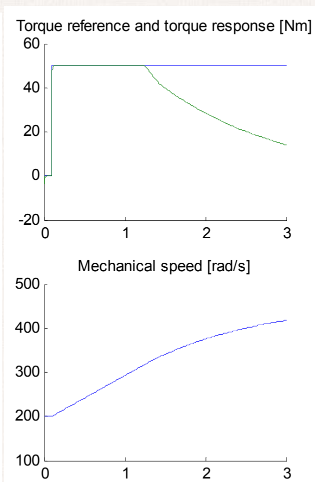

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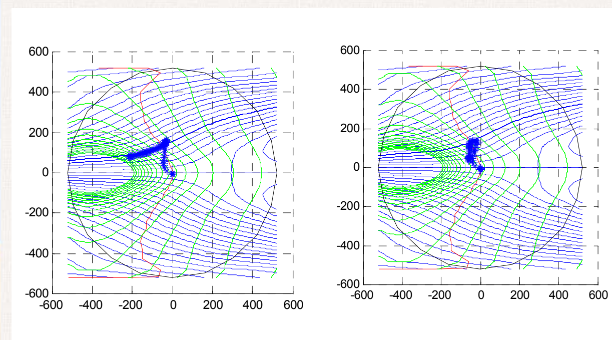

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