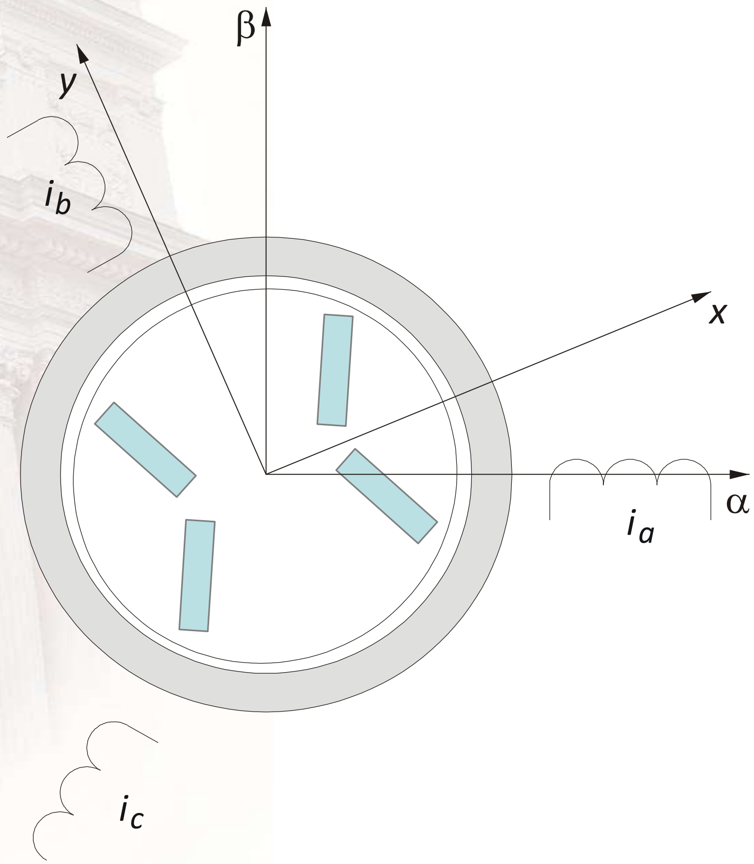
Power Electronics

The Synchronous Machine Control

The PMSM – like the ideal 3-phase load



$$
\begin{aligned}
&\sqrt{\frac{2}{3}}\left(u_{sa} = R_s \cdot i_{sa} + \frac{d\psi_{sa}}{dt} \right) \\
&\sqrt{\frac{2}{3}} \cdot e^{j\frac{2\pi}{3}} \cdot \left(u_{sb} = R_s \cdot i_{sb} + \frac{d\psi_{sb}}{dt} \right) \\
+ \; &\sqrt{\frac{2}{3}} \cdot e^{j\frac{2\pi}{3}} \cdot \left(u_{sc} = R_s \cdot i_{sc} + \frac{d\psi_{sc}}{dt} \right) \\
\hline
&\vec{u}_s = R_s \cdot \vec{i}_s + \frac{d\vec{\psi}_s}{dt}
\end{aligned}
$$

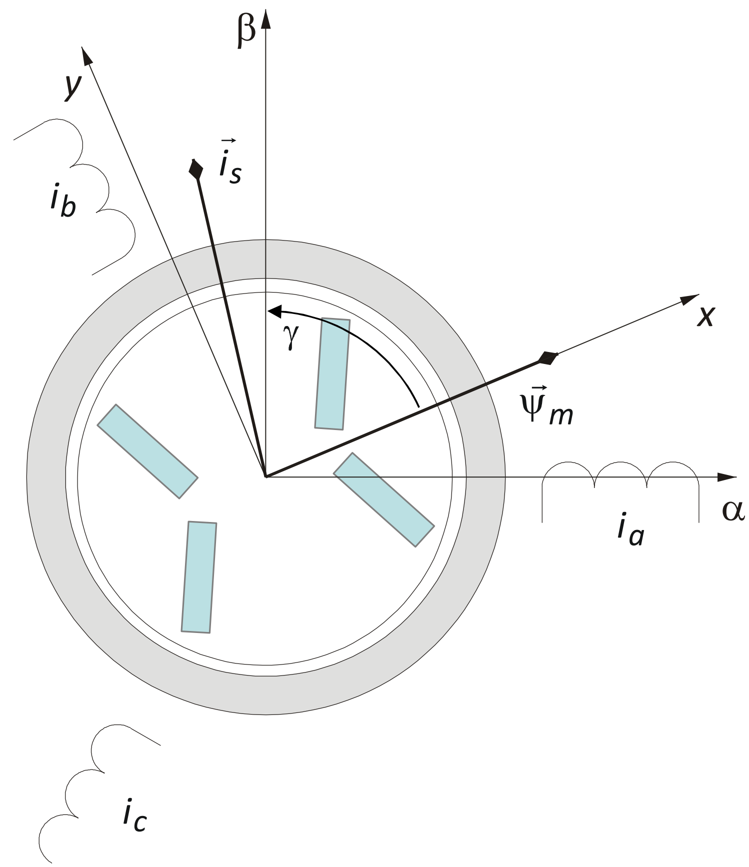
Mathematical Model – Voltage and Current

- **The PMSM has:**
  - ***a 3-phase winding, with resistance and inductance***
  - ***A back emf***
- **It can be described with the same equation as the ideal 3-phase load – in the ROTOR reference frame (*x*,*y*)**

$$\vec{u}_s = R_s \cdot \vec{\imath} + L_s \cdot \frac{d\vec{\imath}}{dt} + \boxed{j \cdot \omega \cdot L_s \cdot \vec{\imath}} + \vec{e}_s$$

$$\vec{e}_s = \boxed{j \cdot \omega_{el} \cdot \psi_m}$$

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



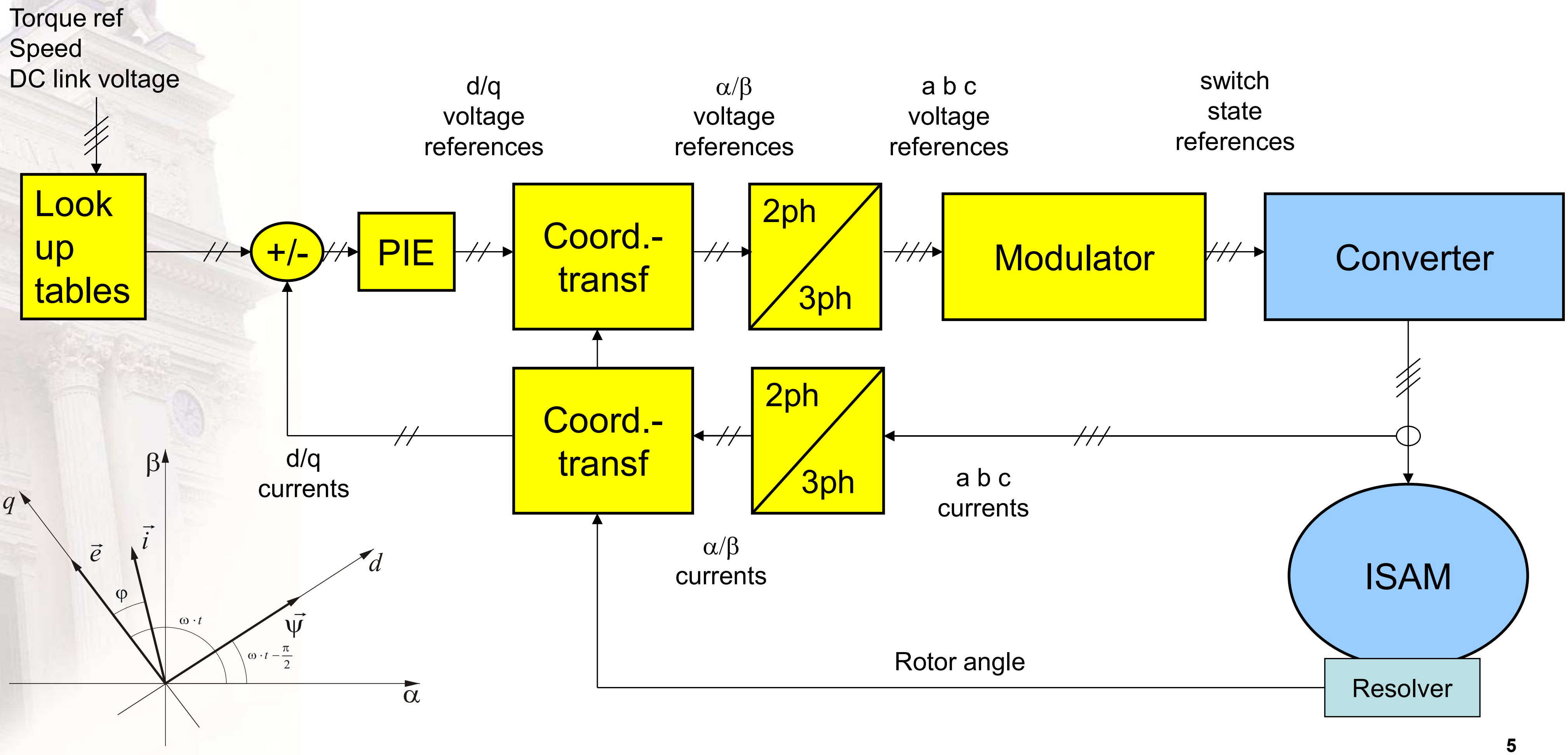
3-phase sampled vector control : 4

Components:

$$u_{sx}^{*}(k)=\left(\frac{L_s}{T_s}+\frac{R}{2}\right)\cdot\left(\left(i_{sx}^{*}(k)-i_{sx}(k)\right)+\frac{T_s}{\left(\frac{L_s}{R_s}+\frac{T_s}{2}\right)}\cdot\sum_{n=0}^{n=k-1}\left(i_{sx}^{*}(n)-i_{sx}(n)\right)\right)-\omega_{el}\cdot L\cdot i_{sy}(k)$$

$$u_{sy}^{*}(k)=\left(\frac{L_s}{T_s}+\frac{R}{2}\right)\cdot\left(\left(i_{sy}^{*}(k)-i_{sy}(k)\right)+\frac{T_s}{\left(\frac{L_s}{R_s}+\frac{T_s}{2}\right)}\cdot\sum_{n=0}^{n=k-1}\left(i_{sy}^{*}(n)-i_{sy}(n)\right)\right)+\omega_{el}\cdot L\cdot i_{sx}(k)+e_{sy}(k)$$

Control in a rotating reference frame

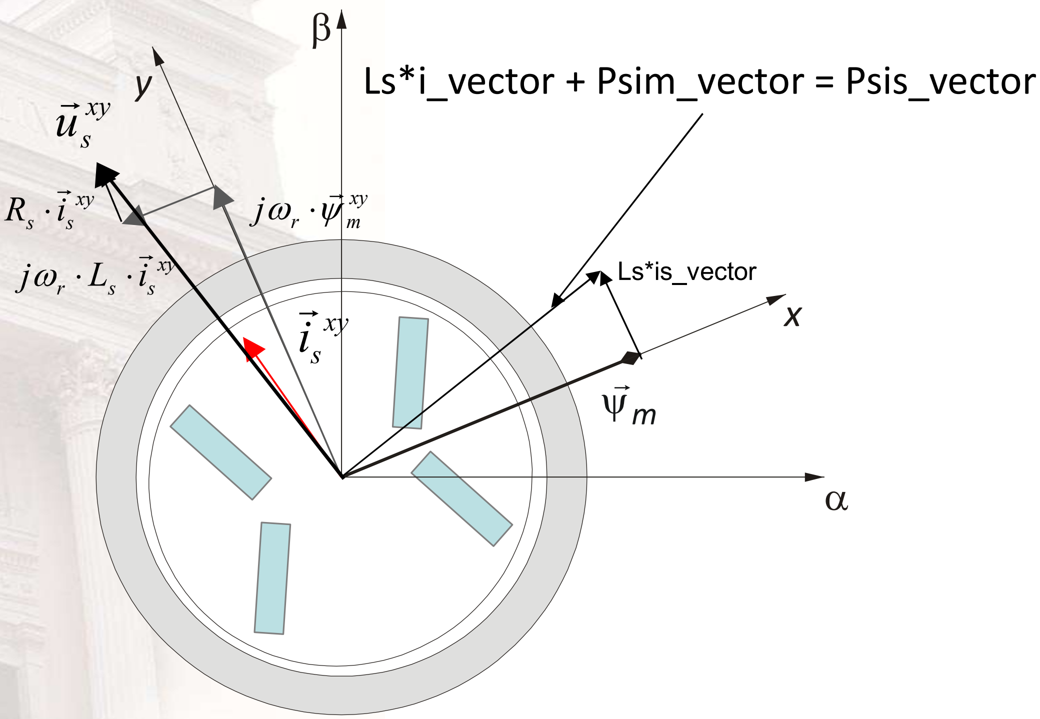


PMSM Torque Control

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

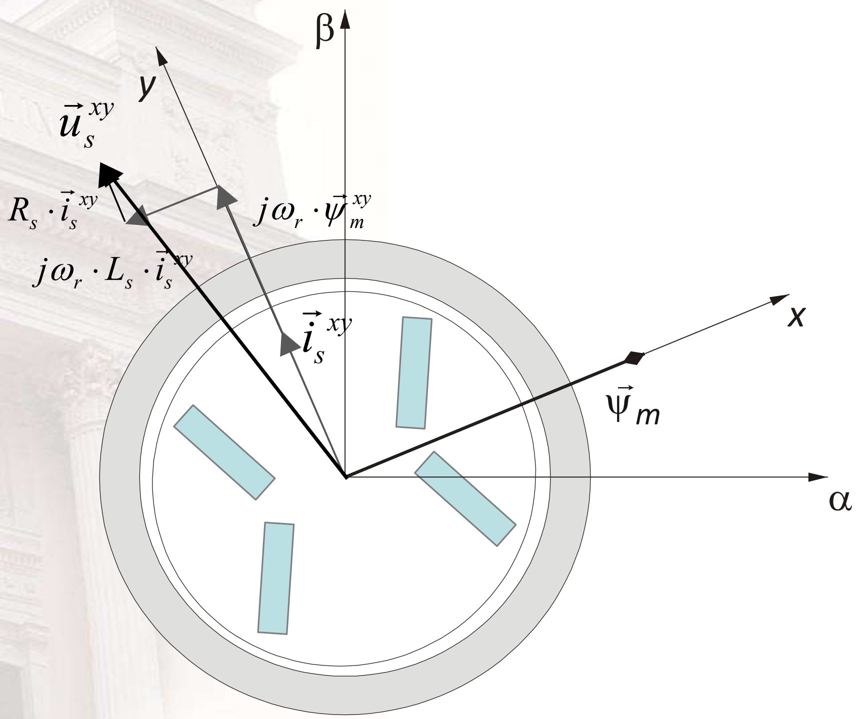
$$= (\psi_m + L_{sx} \cdot i_{sx}) \cdot i_{sy} - L_{sy} \cdot i_{sy} \cdot i_{sx} =$$

$$= \underbrace{\psi_m \cdot i_{sy}}_{\text{Lorenz torque}} + \underbrace{(L_{sx} - L_{sy}) \cdot i_{sx} \cdot i_{sy}}_{\text{Reluctance torque}}$$



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

Simplest, only y-axis current control

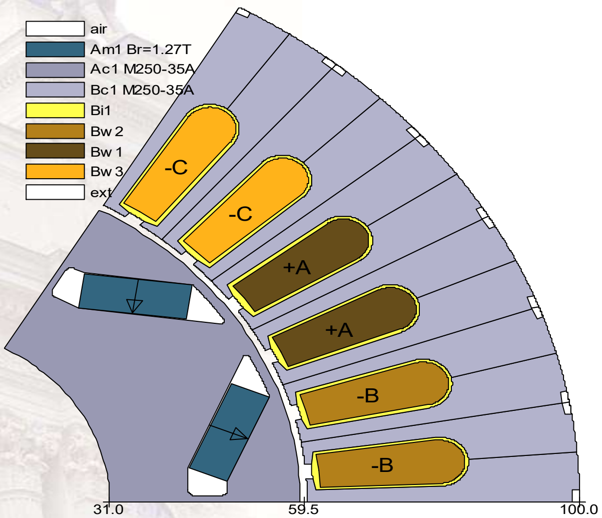


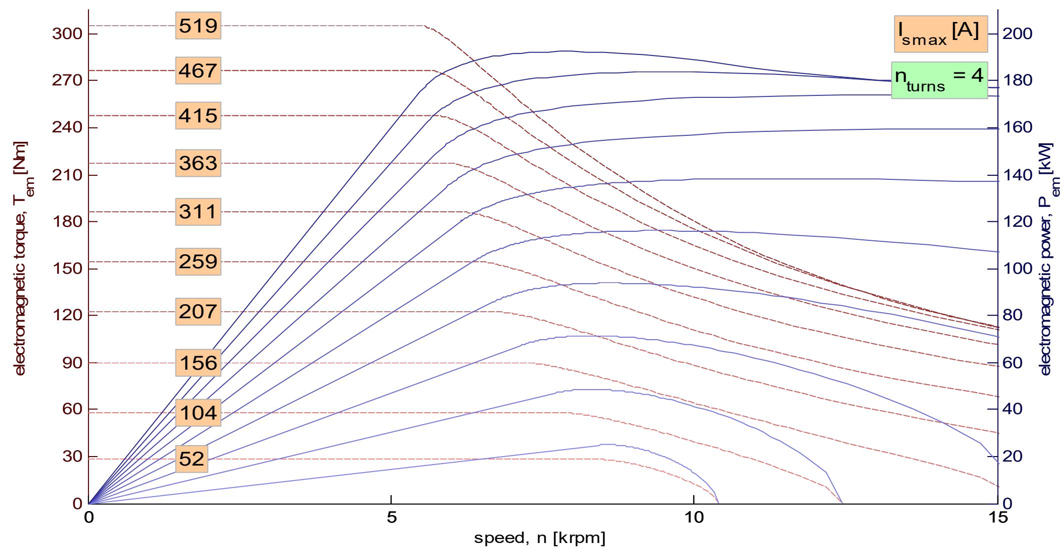
$$T = \psi_m \cdot i_{sy} + (L_{sx} - L_{sy}) \cdot i_{sx} \cdot i_{sy}$$

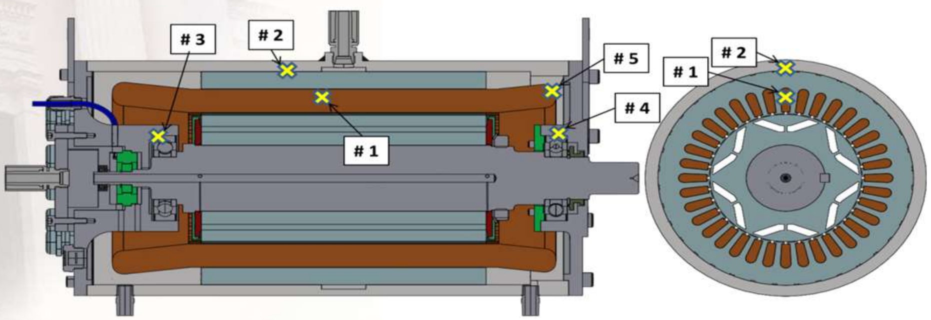
$$\begin{cases} i_{sx}^* = 0 \\ i_{sy}^* = \dfrac{T^*}{\psi_m} \end{cases}$$

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

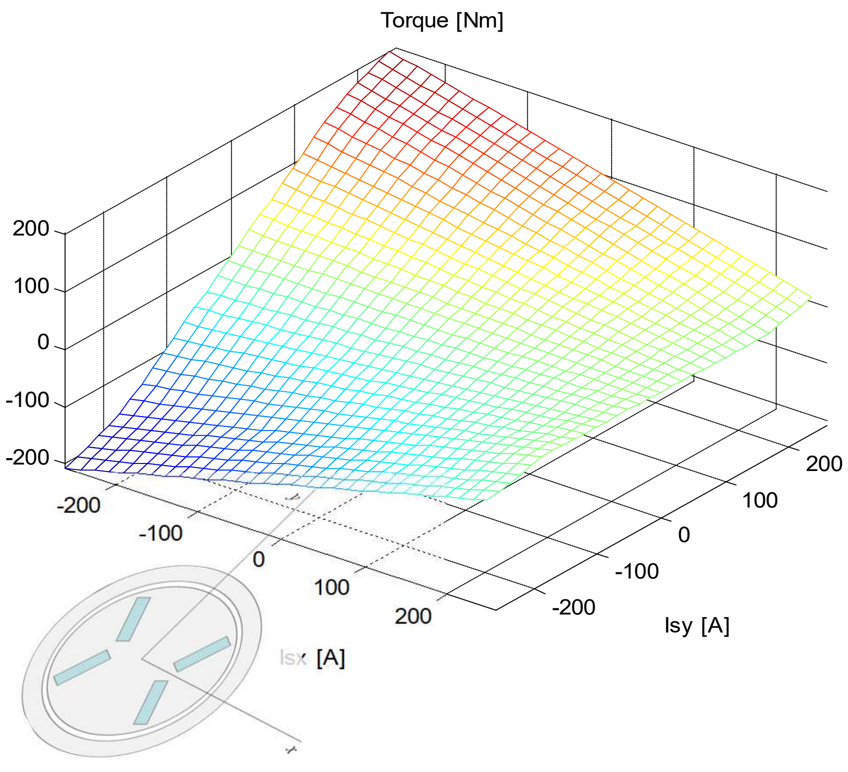
Example: Rasmus Andersson’s ExSAM

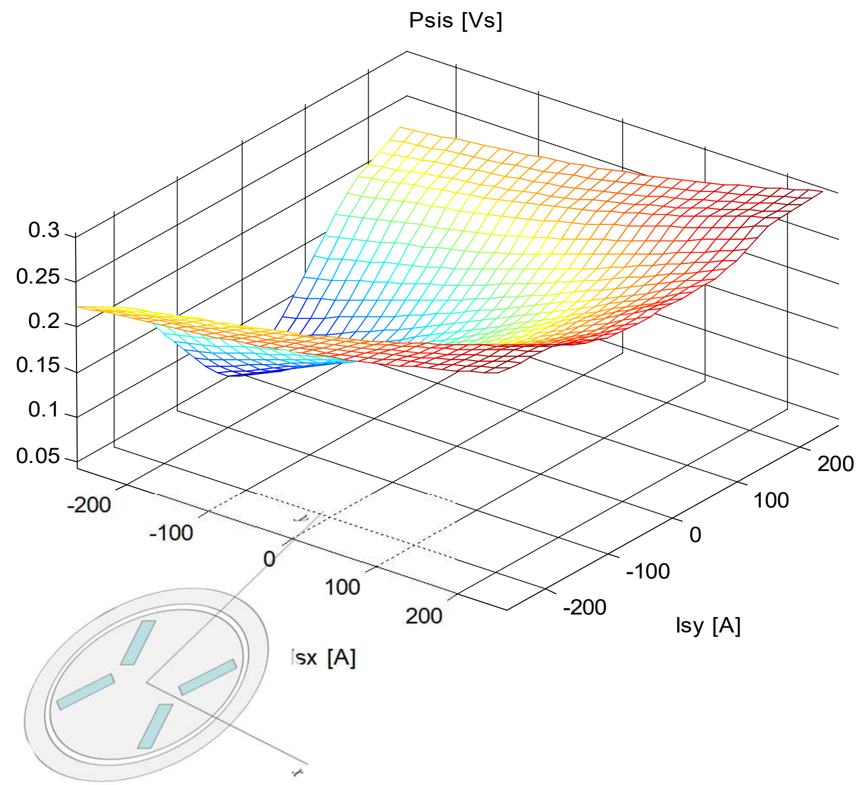




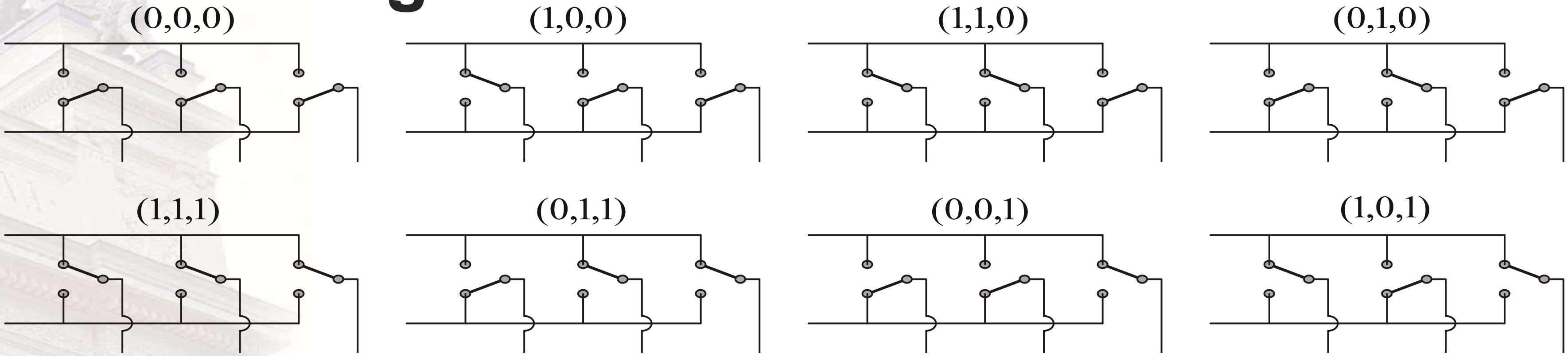


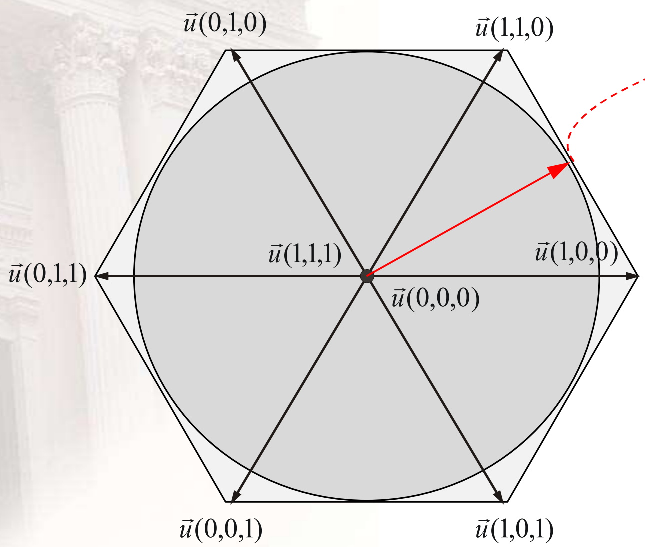
Torque & Stator Flux Linkage





Stator Voltage limitation





$$\vec{u}(1,0,0) = \sqrt{\frac{2}{3}}U_{dc} = -\vec{u}(0,1,1)$$

$$\vec{u}(0,1,0) = \sqrt{\frac{2}{3}}U_{dc} \cdot e^{j\frac{2\cdot\pi}{3}} = -\vec{u}(1,0,1)$$

$$\vec{u}(0,0,1) = \sqrt{\frac{2}{3}}U_{dc} \cdot e^{j\frac{4\cdot\pi}{3}} = -\vec{u}(1,1,0)$$

$$\vec{u}(0,0,0) = 0 = \vec{u}(1,1,1)$$

$$\left|\vec{u}_s^{xy}\right| \sqrt{\frac{2}{3}}_{dc} \cos\left(\frac{\pi}{6}\right)_{\max}$$

$$= \sqrt{\frac{2}{3}} \cdot U_{dc} \cdot \frac{\sqrt{3}}{2} = \frac{U_{dc}}{\sqrt{2}}$$

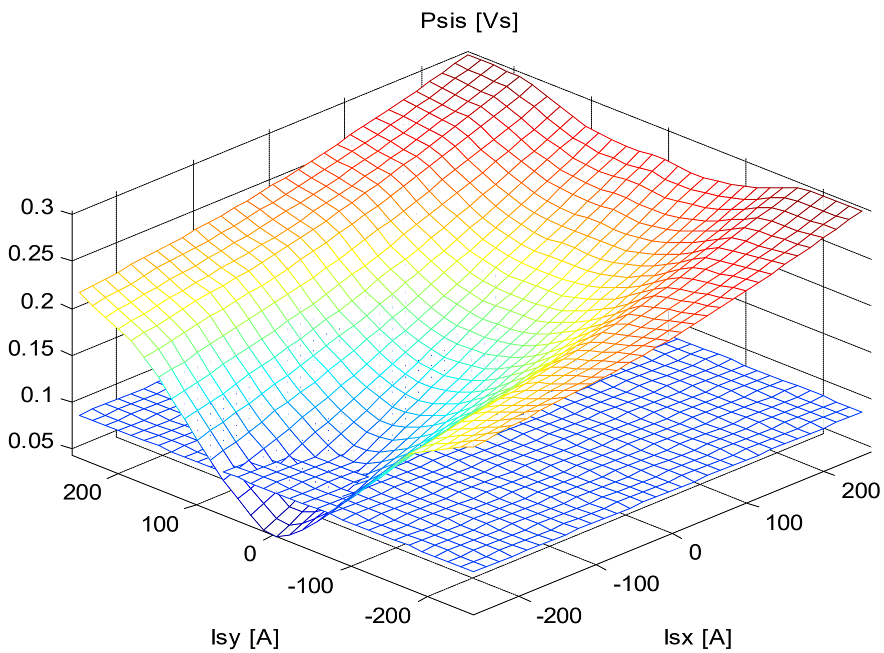
Stator Flux Linkage limitation : I

$$
\begin{aligned}
|\vec{u}_s| &= \sqrt{\left(R_s \cdot i_{sx} - \omega_{r,el} \cdot L_{sy} \cdot i_{sy}\right)^2 + \left(R_s \cdot i_{sy} + \omega_{r,el} \cdot (\psi_m + L_{sx} \cdot i_{sx})\right)^2} \approx \\
&\approx \sqrt{\left(\omega_{r,el} \cdot L_{sy} \cdot i_{sy}\right)^2 + \left(\omega_{r,el} \cdot (\psi_m + L_{sx} \cdot i_{sx})\right)^2} = \\
&= \omega_{r,el} \cdot \sqrt{\left(L_{sy} \cdot i_{sy}\right)^2 + (\psi_m + L_{sx} \cdot i_{sx})^2} = \\
&= \omega_{r,el} \cdot \sqrt{\left(\psi_{sy}\right)^2 + (\psi_{sx})^2} = \omega_{r,el} \cdot |\vec{\psi}_s| \leq \frac{U_{dc}}{\sqrt{2}}
\end{aligned}
$$

$$|\vec{\psi}_s| \leq \frac{U_{dc}}{\omega_{r,el} \cdot \sqrt{2}}$$

Example:
U_{dc} = 600 [V]
p = 6 [poles]
N_{max} = 15000 [rpm]
*ω_{el_max} = N_{max}*2*pi/60*p/2 = 4 712 [rad/s] = 750 [Hz]*
P_{sis_min} = U_{dc}/sqrt(2)/ω_{el_max} = 0.09 [Vs]

Stator Flux Linkage limitation : II



Example:

U_{dc} = 600 [V]

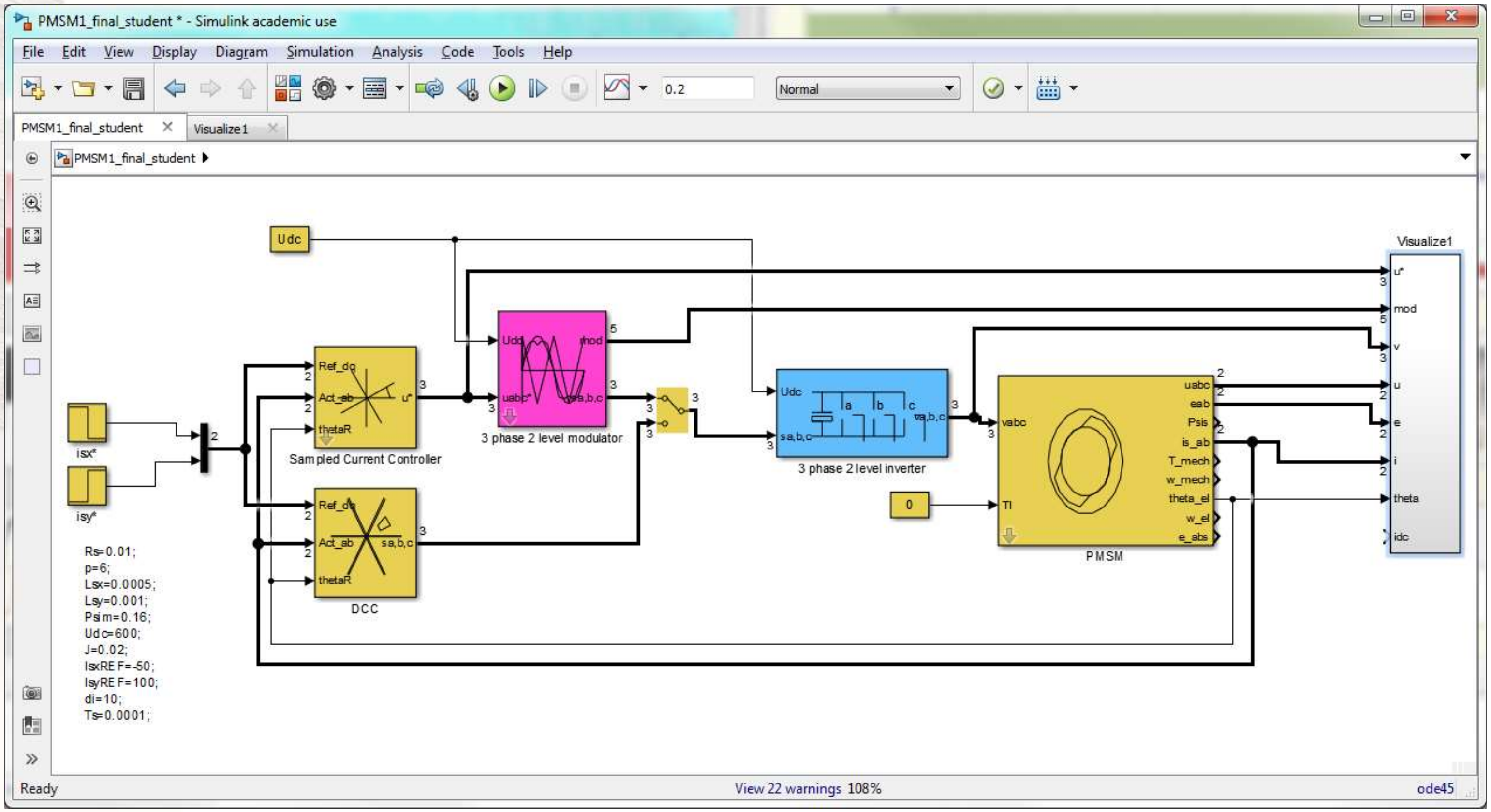
p = 6 [poles]

N_{max} = 15000 [rpm]

$\omega_{el\_max} = N_{max}*2*pi/60*p/2$ = 4 712 [rad/s] = 750 [Hz]

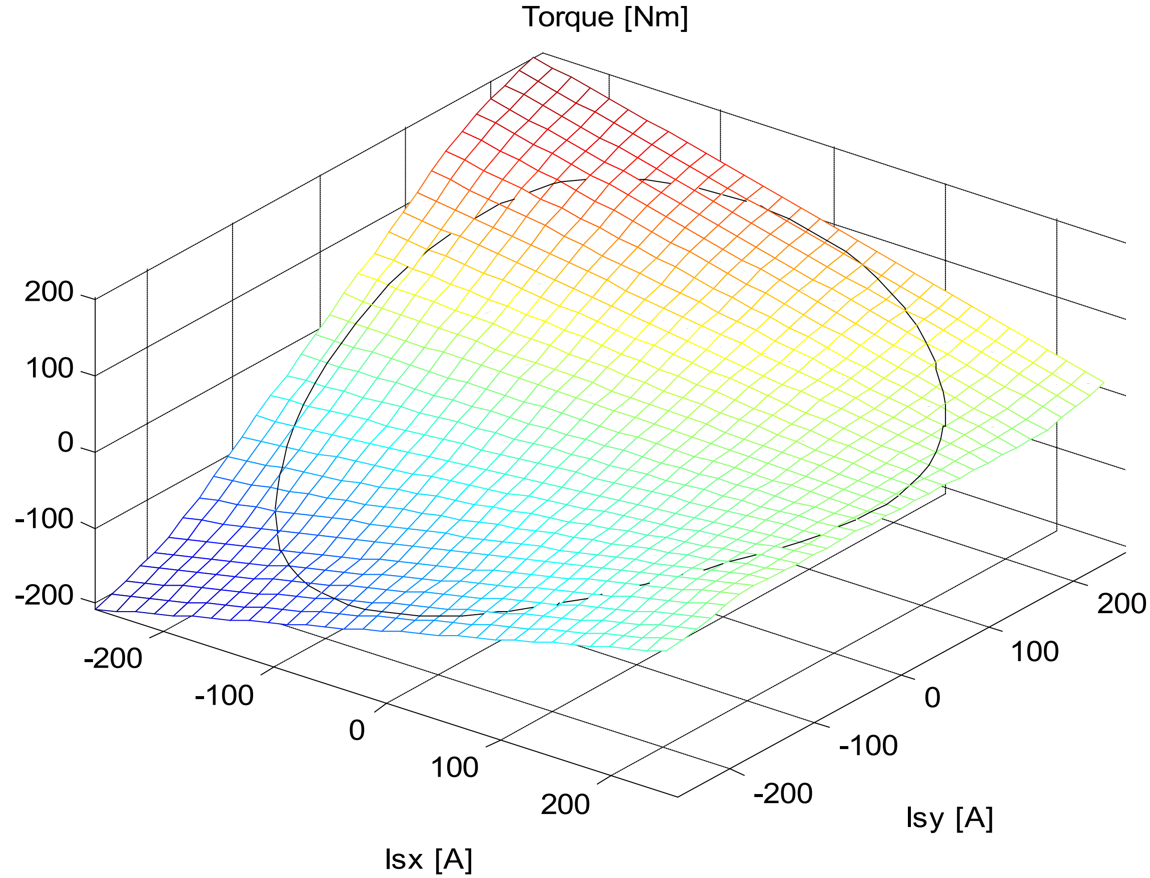
$P_{sis\_min} = U_{dc}/sqrt(2)/\omega_{el\_max}$ = 0.09 [Vs]

Some Simulink



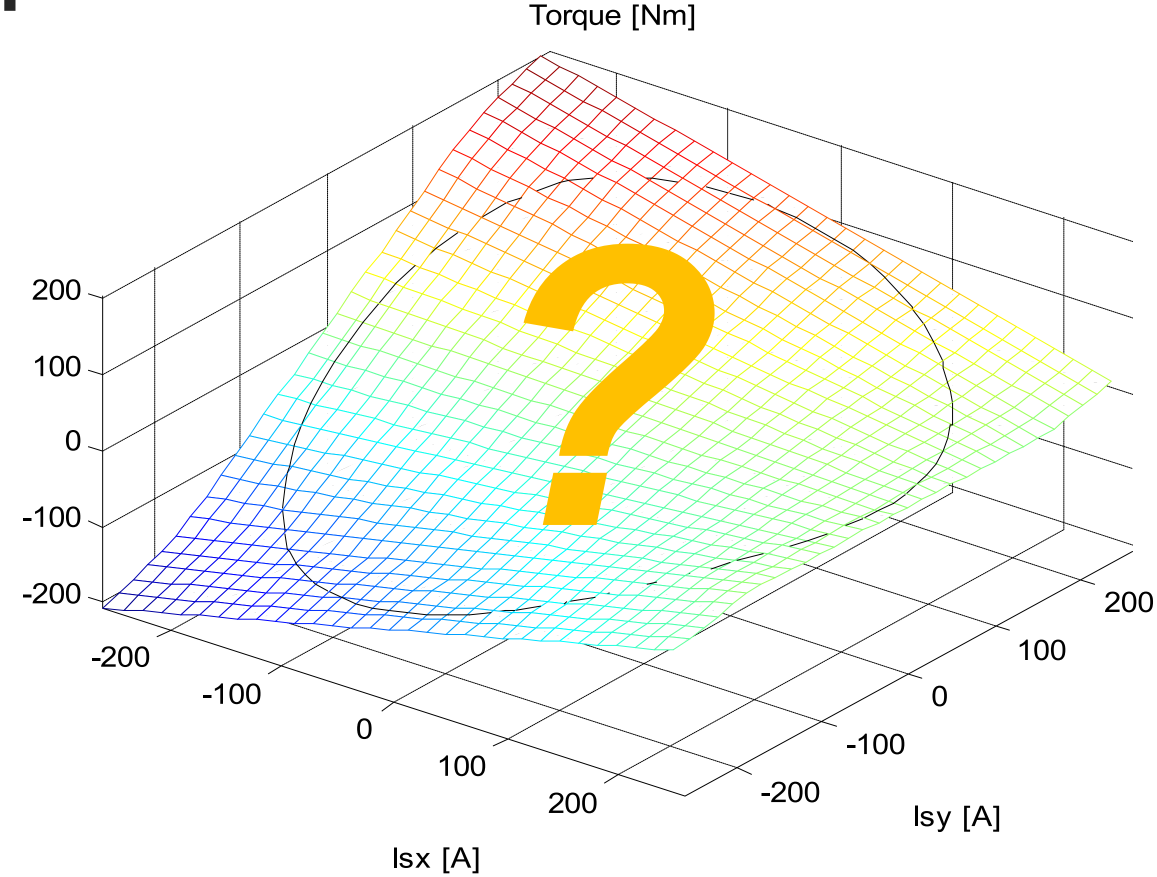
Current Limitation

Limited by the Converter or Motor



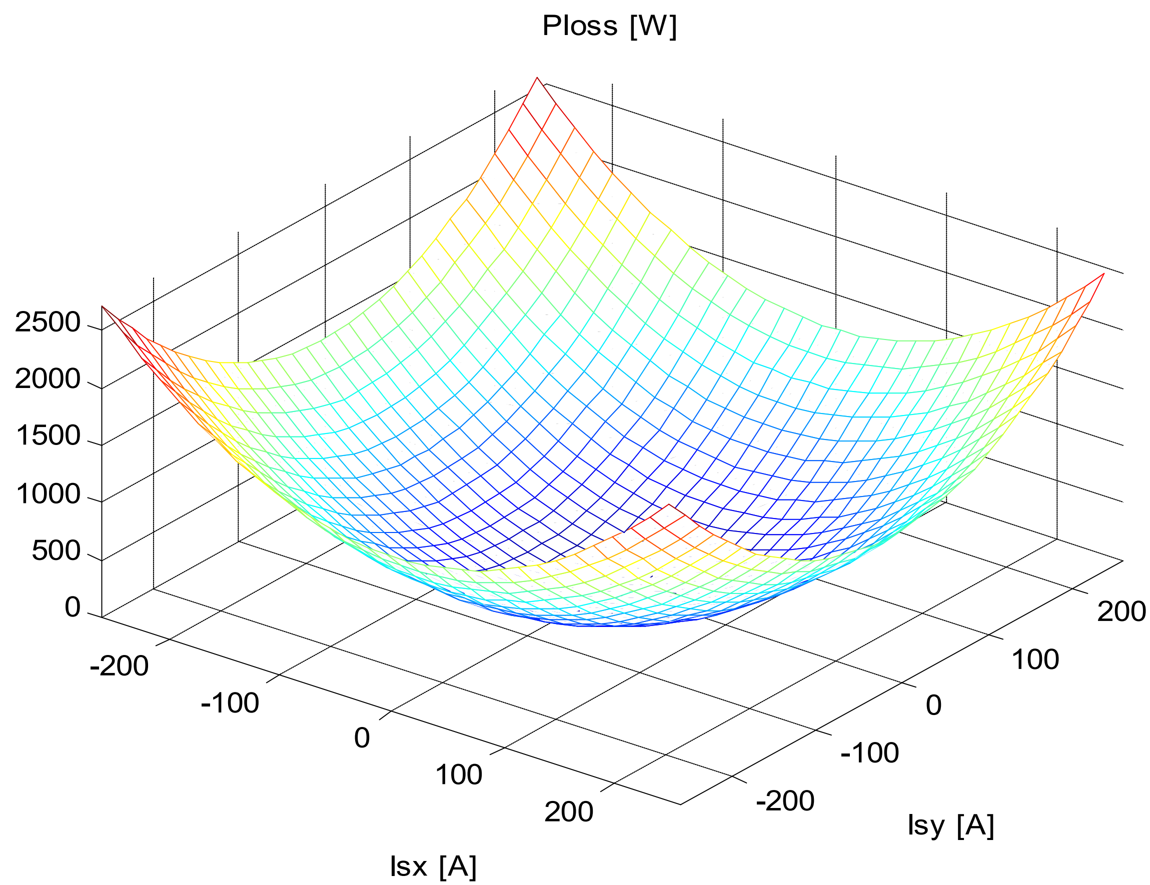
So, where do we position the current ... ?

- **Minimize losses !**
- **What losses?**
  - ***Resistive losses?***
  - ***Iron losses?***
  - ***Converter losses?***
  - ***Other losses?***



Resistive losses

- Losses in the stator winding only
- Not frequency dependent
- Not temp dependent

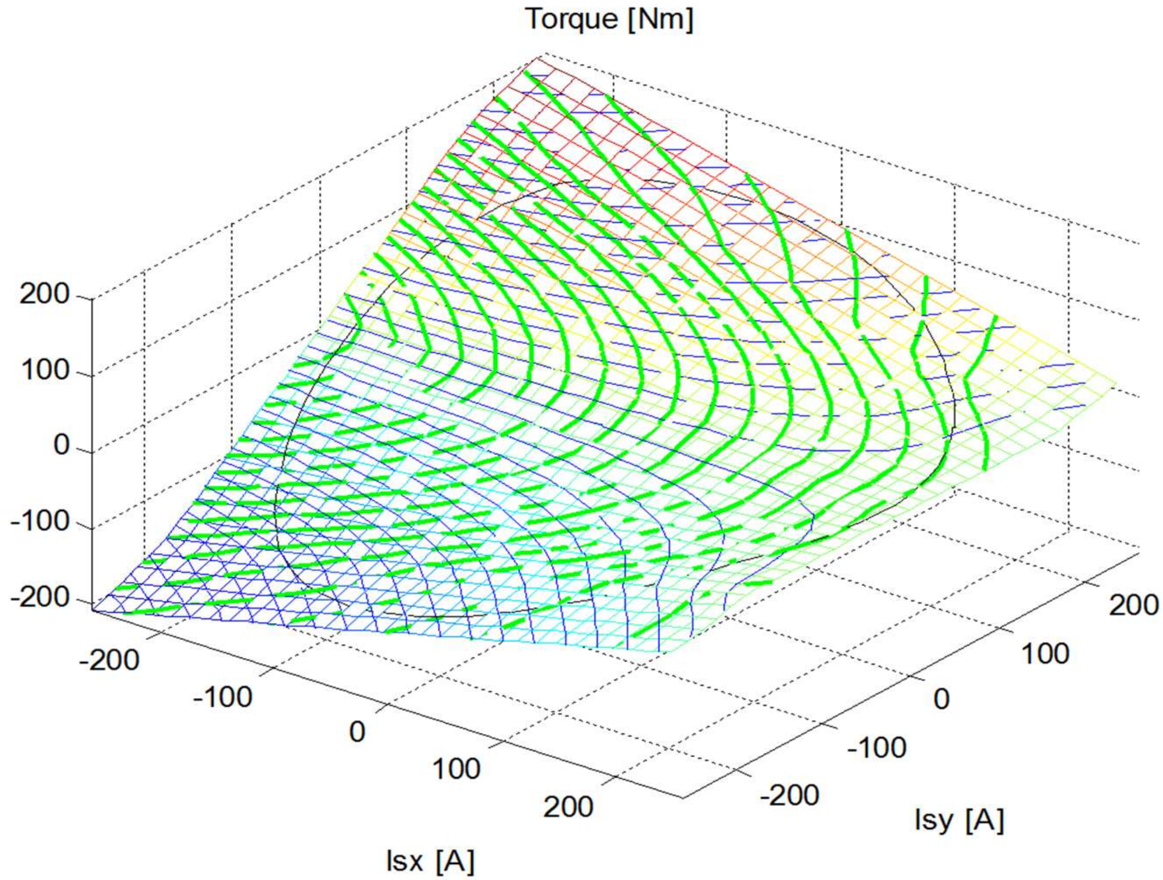


Resistive losses, Torque & Flux

Max
Current

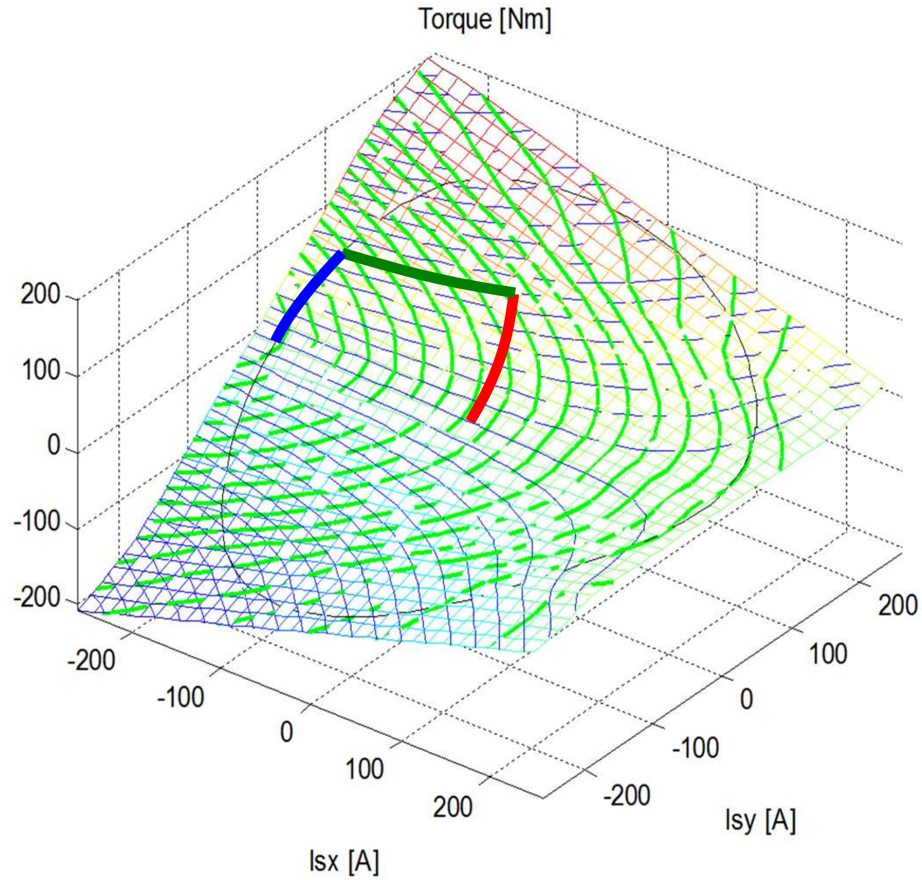
Constant
Torque

Constant Flux
linkage



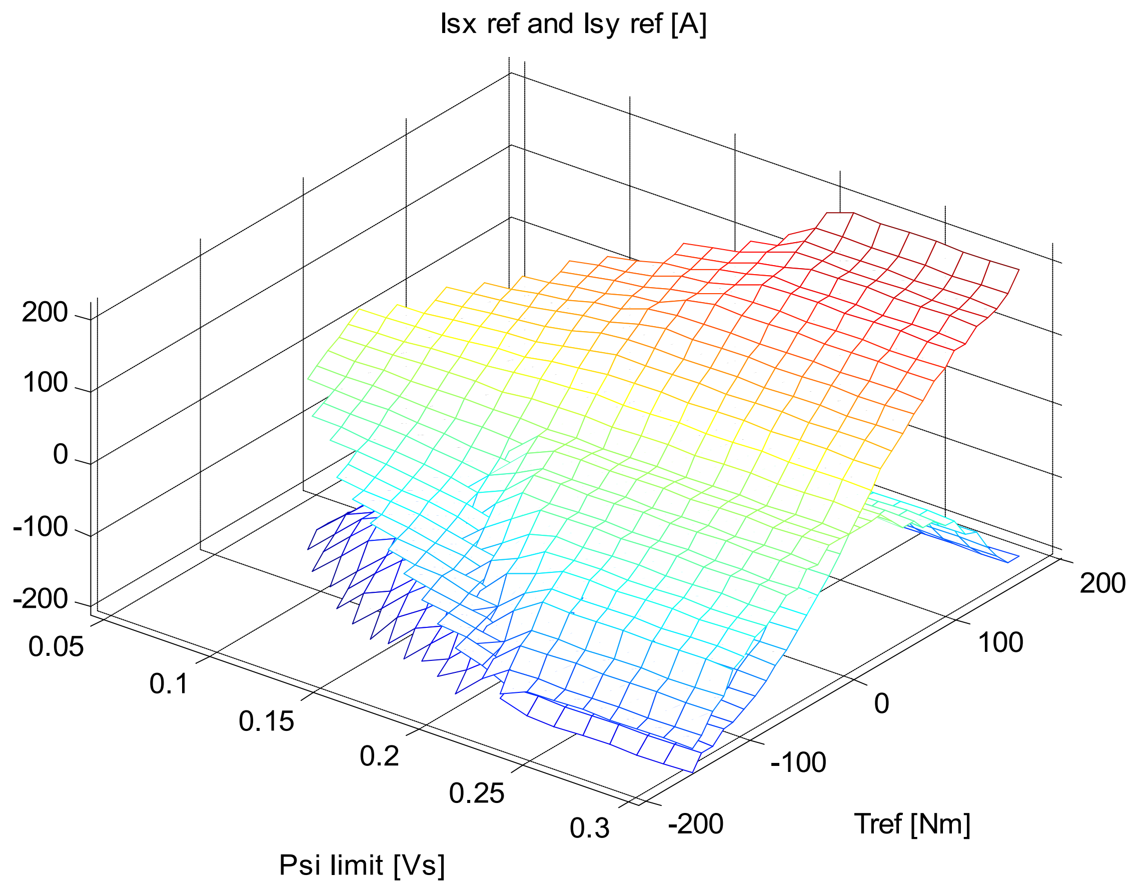
Find the best operating points ...

- **At low speed**
  - *Minimal current for minimal resistive losses*
- **In Voltage limitation**
  - *Follow constant torque until max current*
- **In Current limitation**
  - *Drop torque to respect the voltage limit*



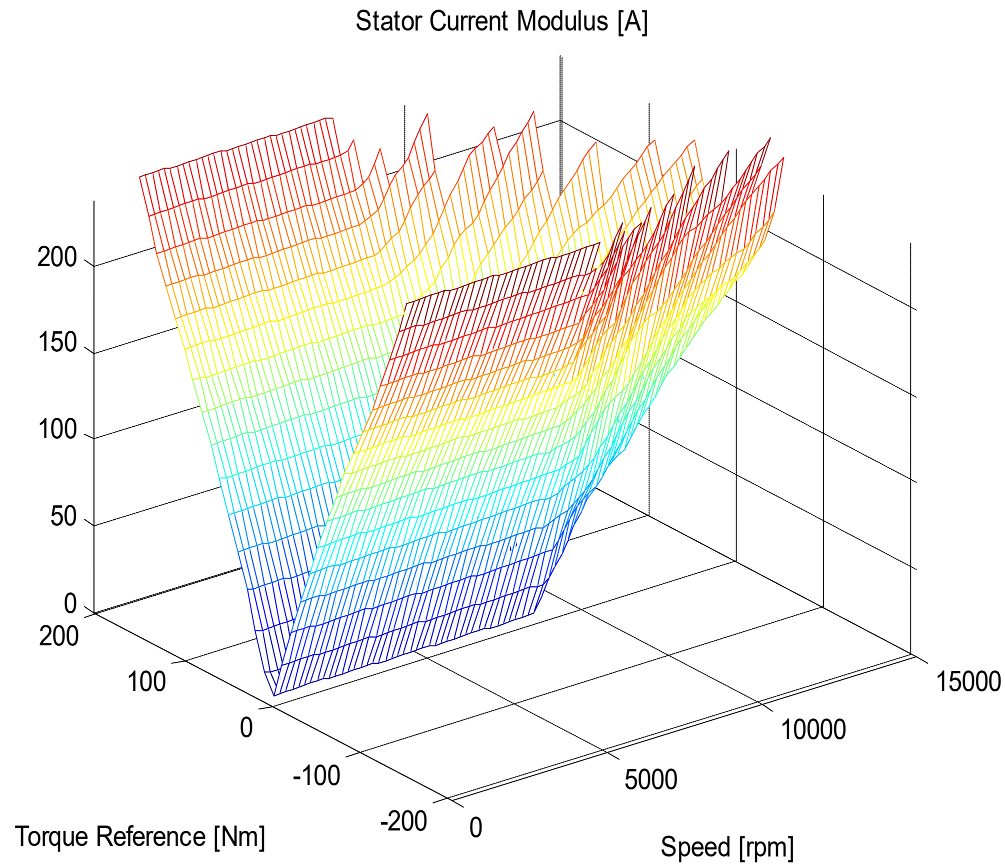
Repeat the search ...

- **For all possible Torque levels**
- **For all possible flux levels**
- **In doing so, for each combination:**
  - ***always select the lowest resistive losses***
  - ***Always respect the current limit***



The drive system performance

- **With the current references known for all torque levels and all flux levels:**
- **For each speed and torque combination:**
  - *Find the Stator flux linkage limit for each speed.*
  - *Select the best currents for the torque & speed combination*
  - *Calculate the losses and limitations i torque*
  - *Plot the Torque Speed Characteristic efficiency etc*



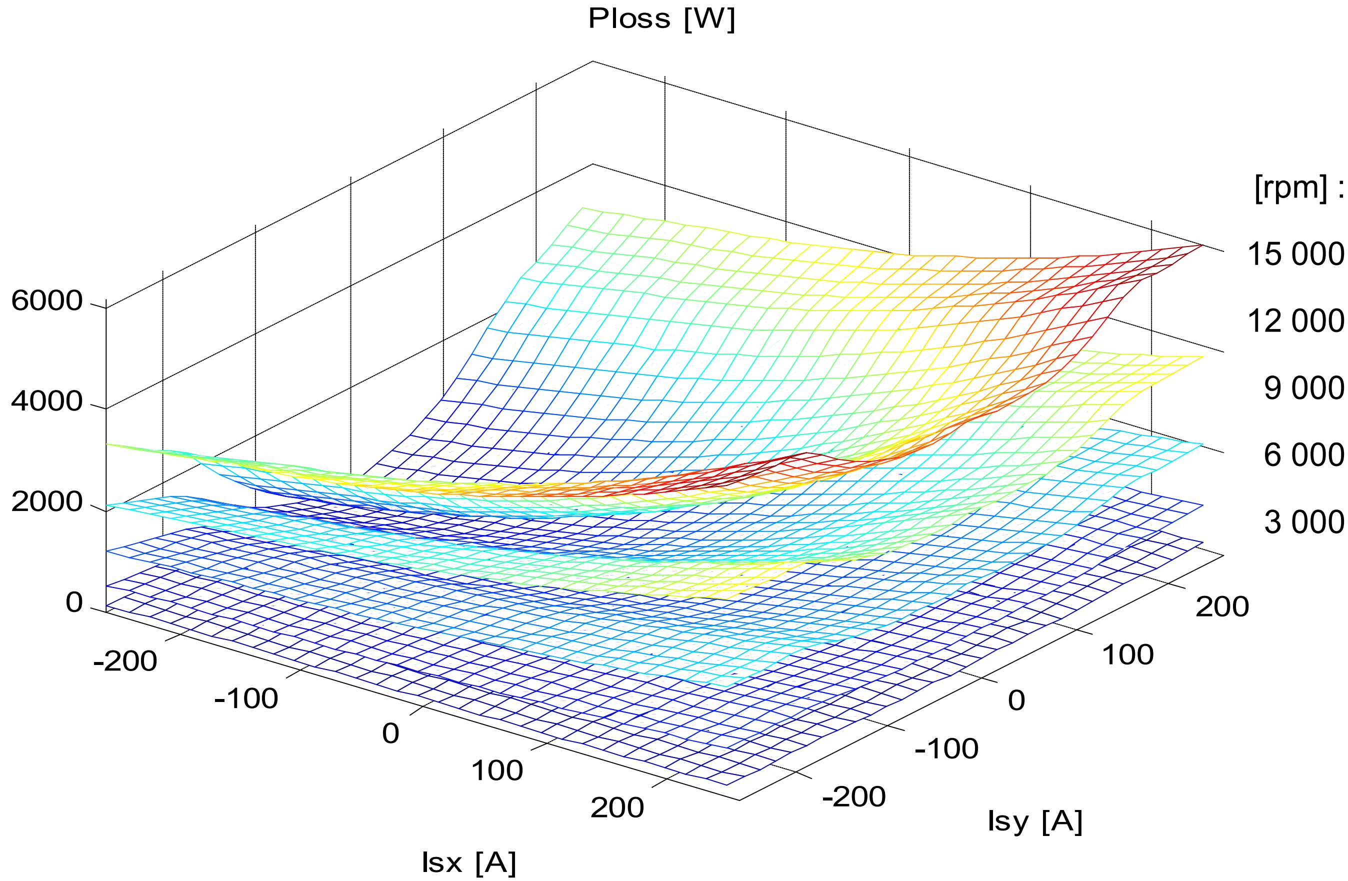
But, there are more than resistive losses ...

e.g.

- **Iron losses**
  - *Here modelled as*

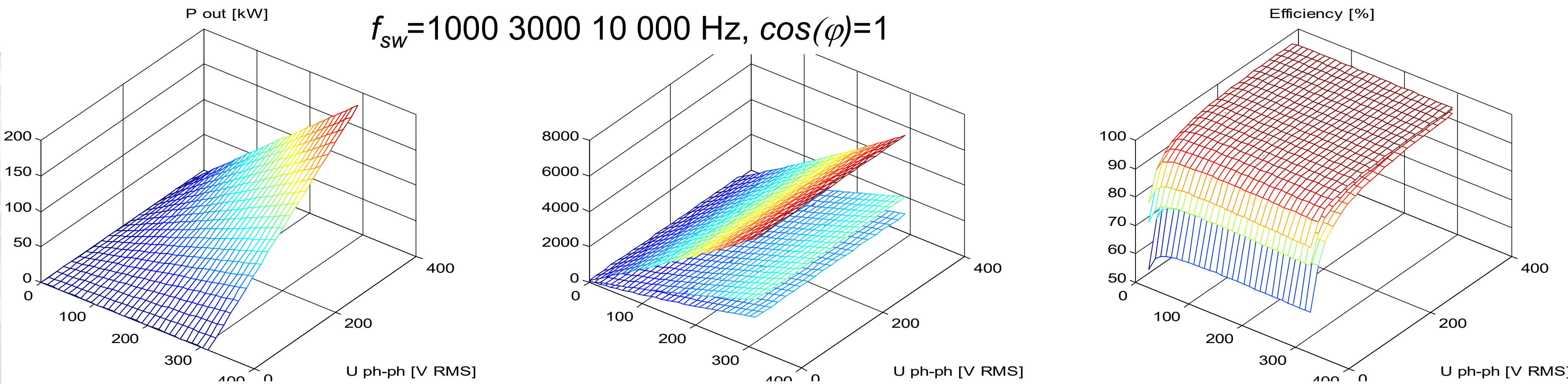
$$P_{fe} = k \cdot (\omega_{r,el} \cdot |\vec{\psi}_s|)^2$$

- **Converter losses**

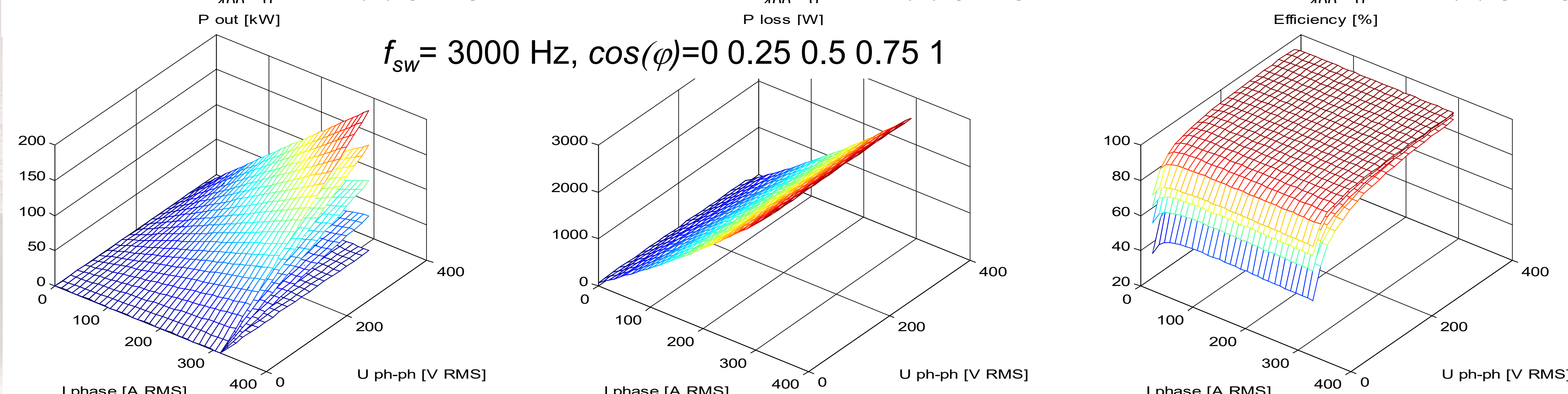


Do you remember the Converter Efficiency ... ?

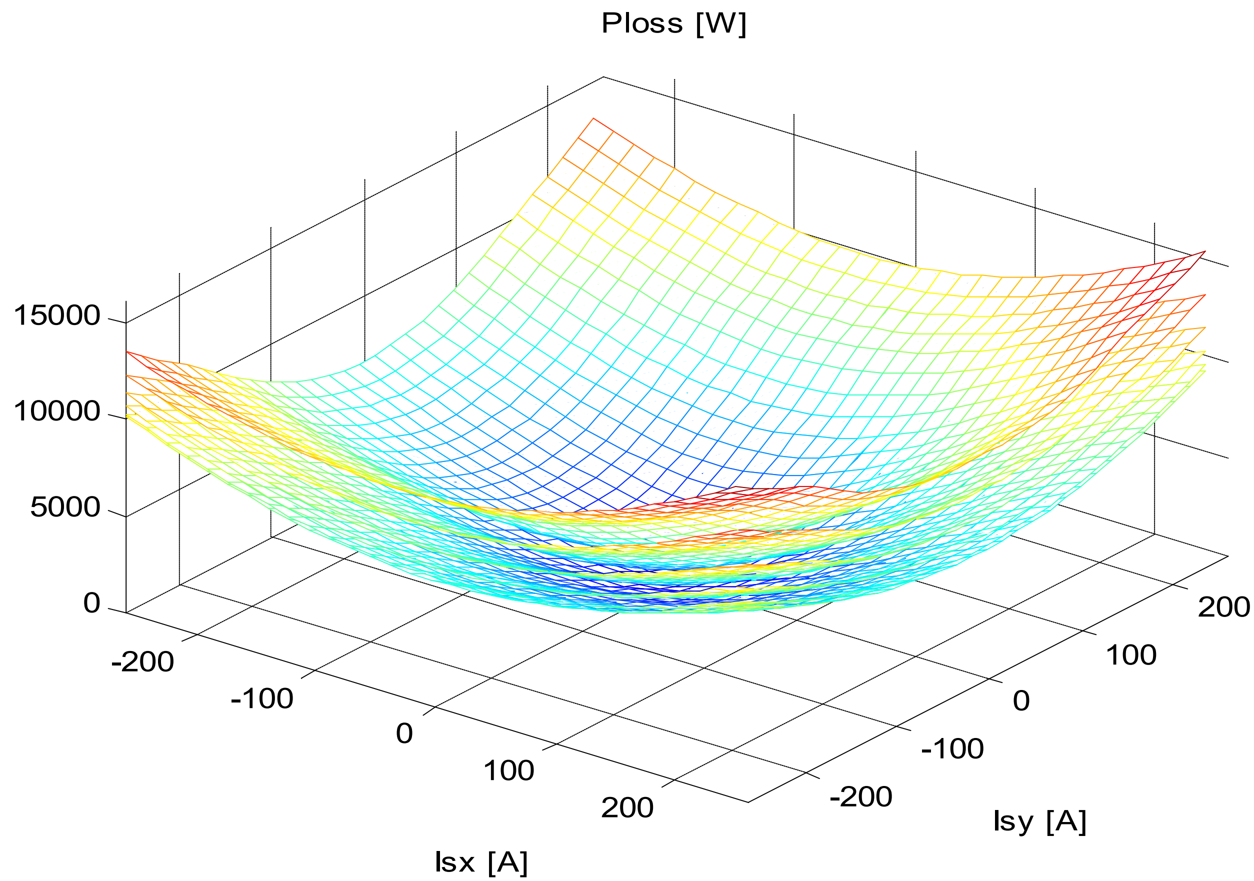
f_{sw}=1000 3000 10 000 Hz, $cos(\varphi)$=1



f_{sw}= 3000 Hz, $cos(\varphi)$=0 0.25 0.5 0.75 1



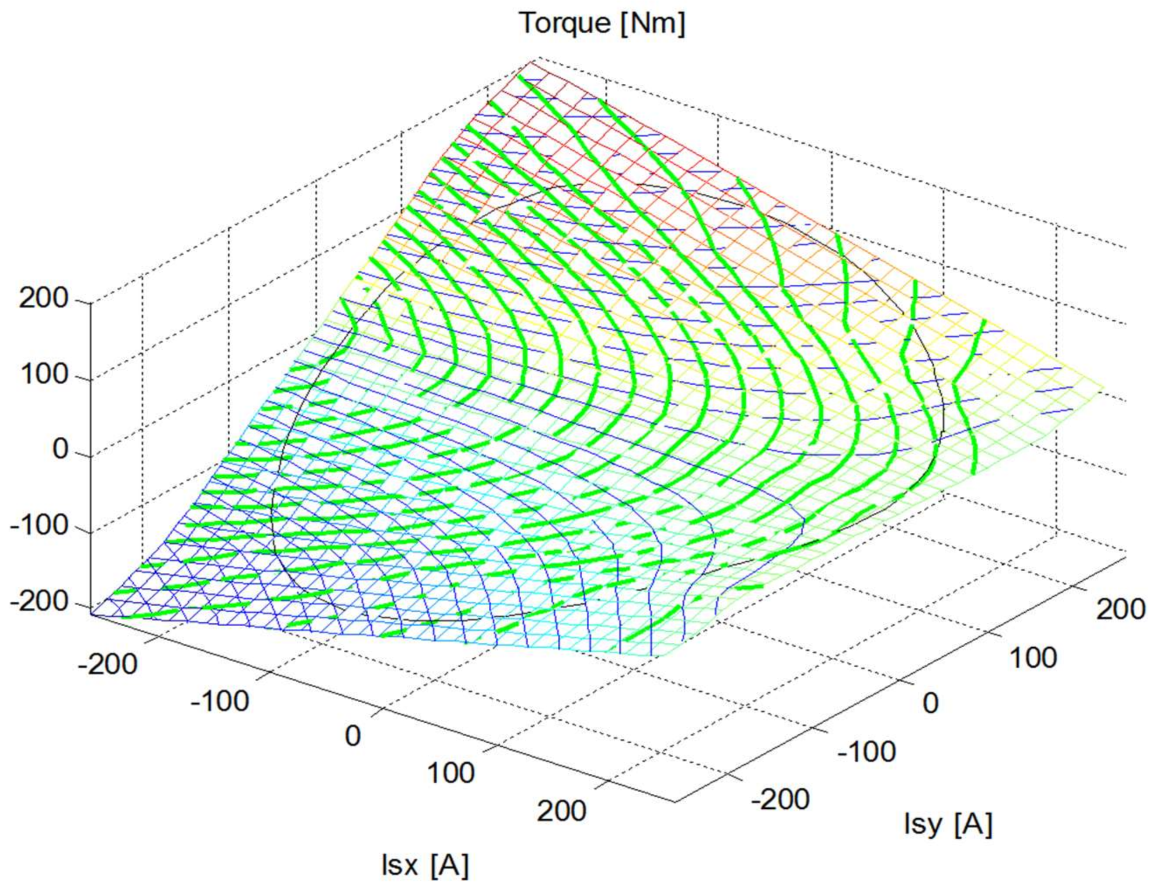
Introduce the new losses, and do it all again ...



Find the best operating points ...

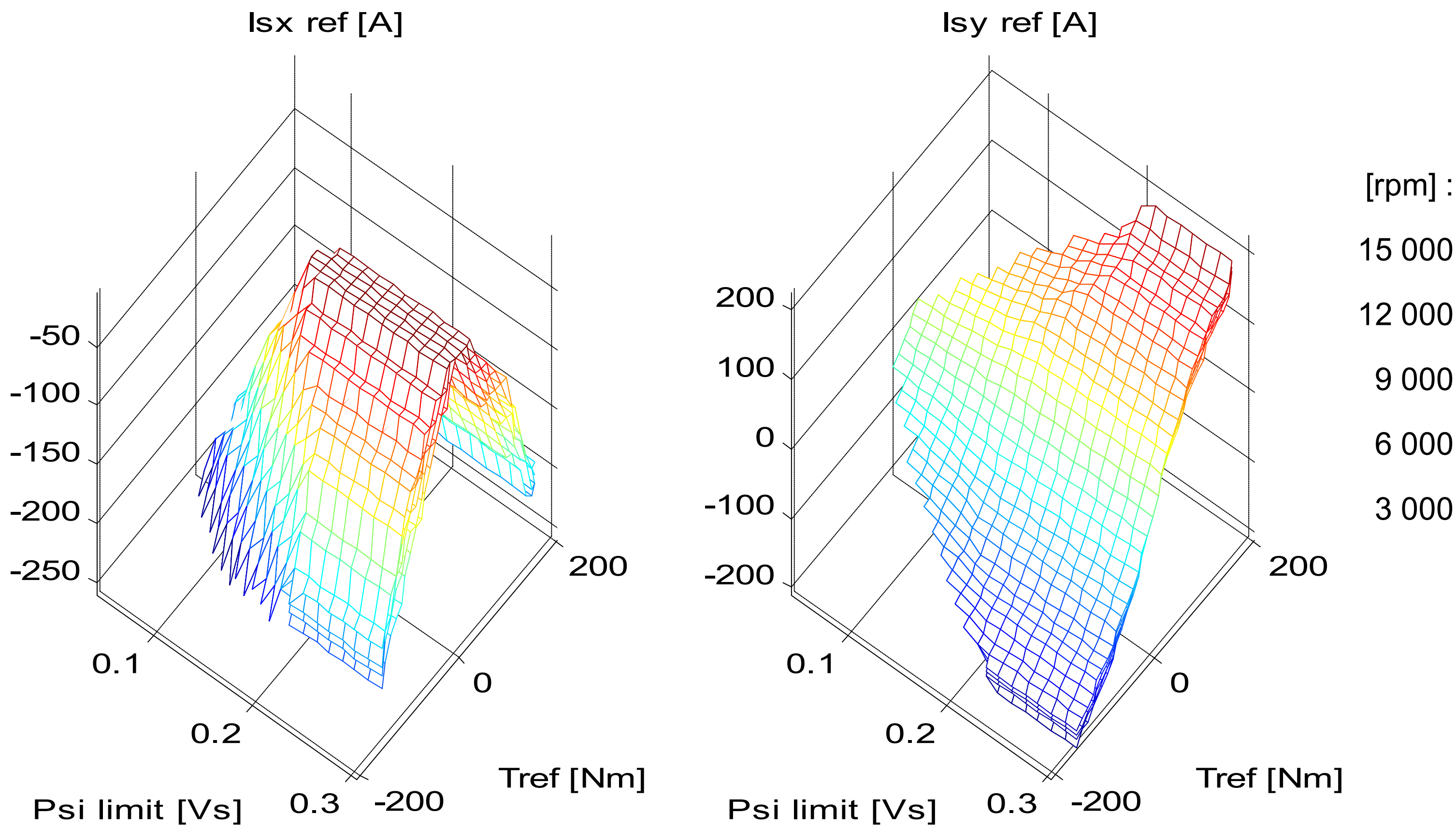
This time:

- *OPTIMAL currents for <u>minimal total losses</u>*
- *Speed differentiates*
  - *Iron losses and Converter losses are speed or voltage dependent*



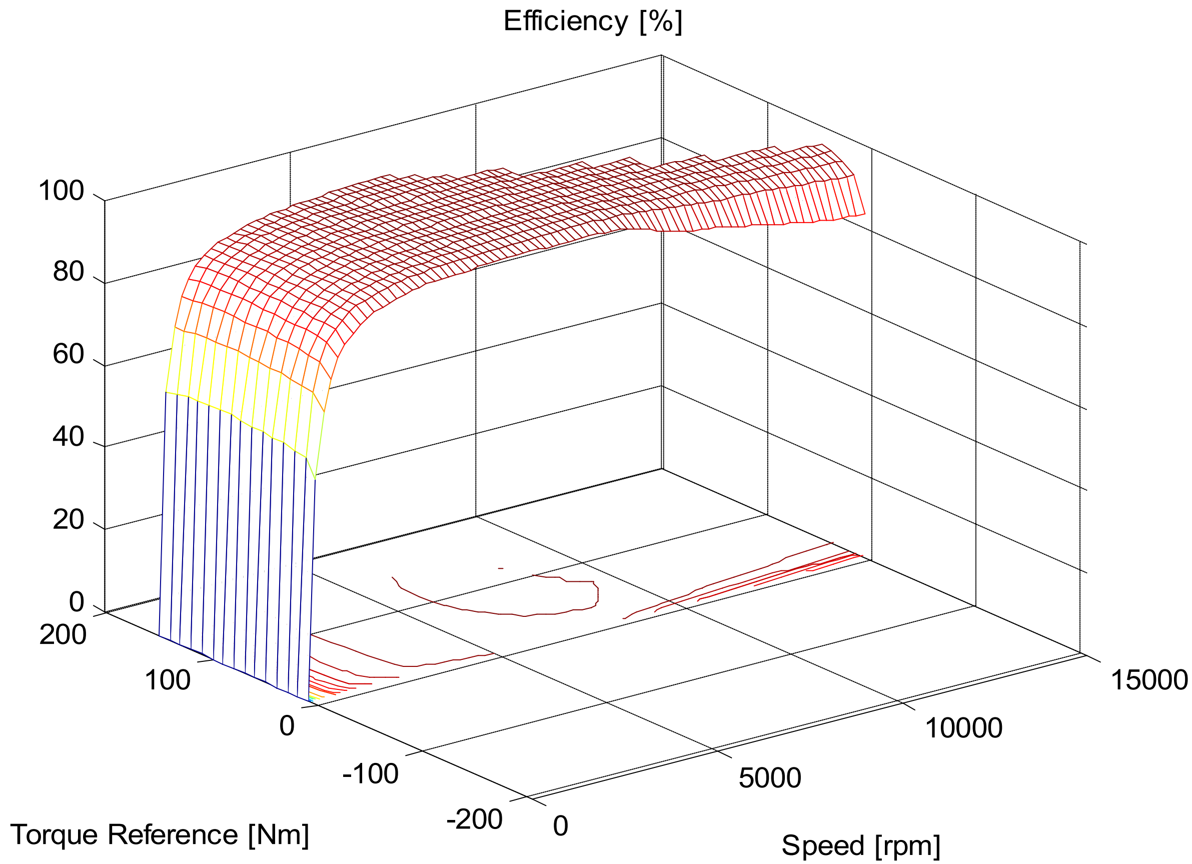
Repeat the search ...

- **For all possible Torque levels**
- **For all possible flux levels**
- **For several different speeds**
- **In doing so, for each combination:**
  - *always select the lowest TOTAL losses*
  - *Always respect the current limit*



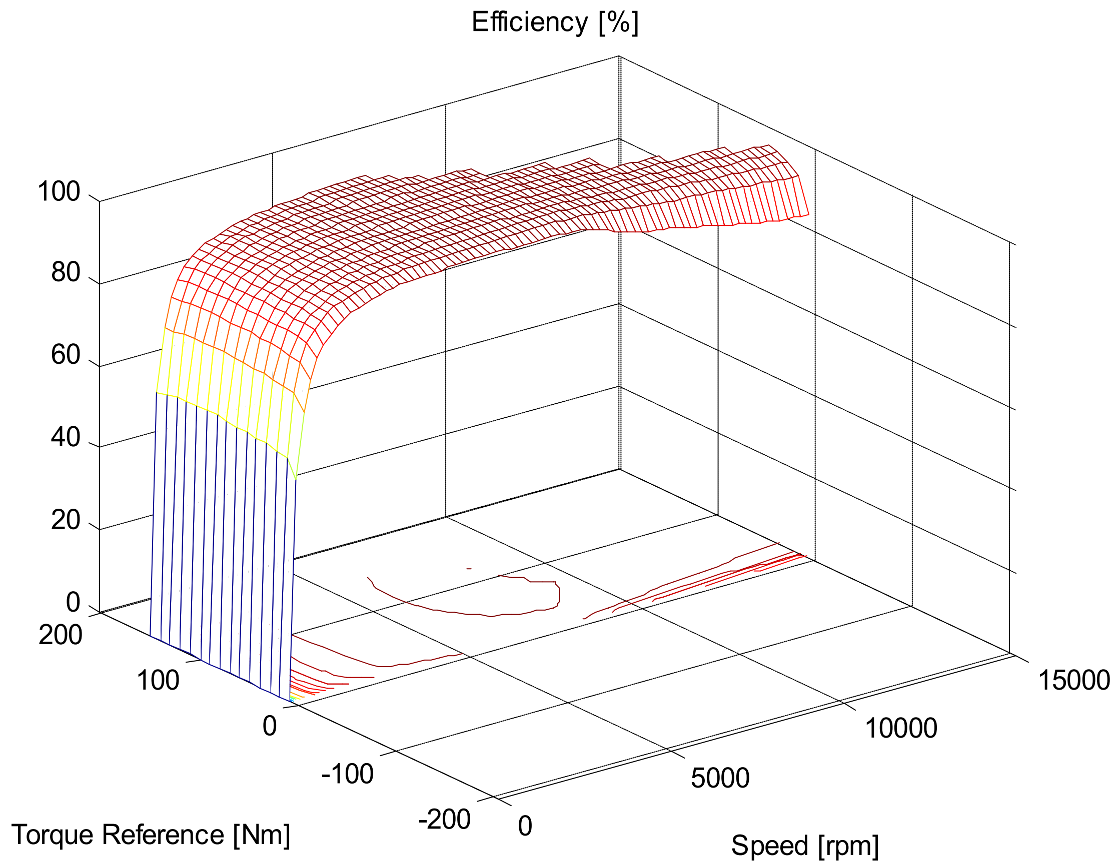
The drive system performance

- **With the current references known for all torque levels and all flux levels:**
- **For each speed and torque:**
  - *Find the Stator flux linkage limit for each speed.*
  - *Select the best currents for the torque & speed combination*
  - *Calculate the losses and limitations in torque*
  - *Plot the Torque Speed Characteristic, efficiency etc*



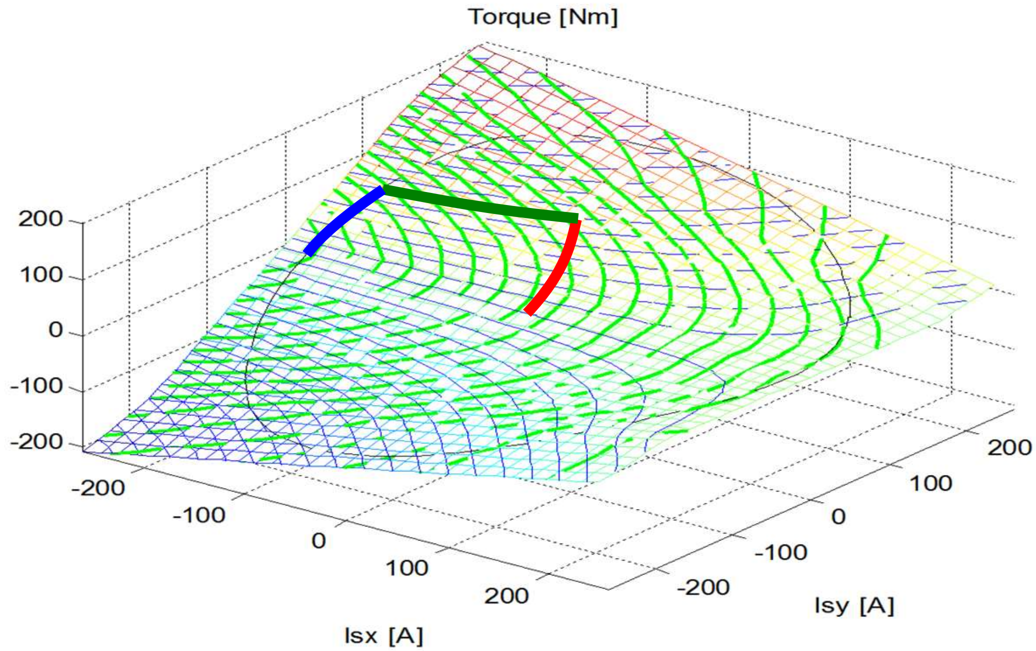
This is the energy optimal drive control !

- It accounts for all losses
- At all possible speed and torque combinations
- ... but we can do more with this information!

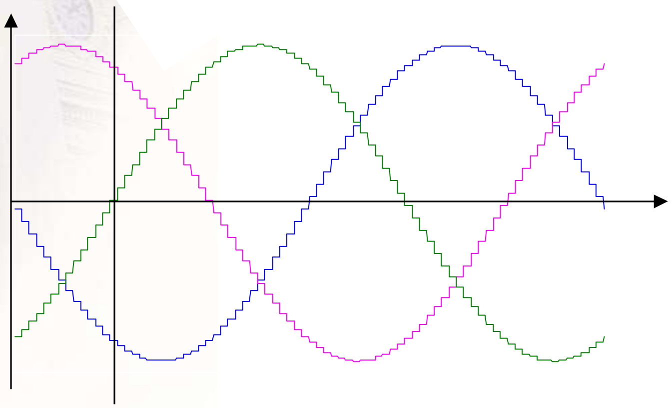


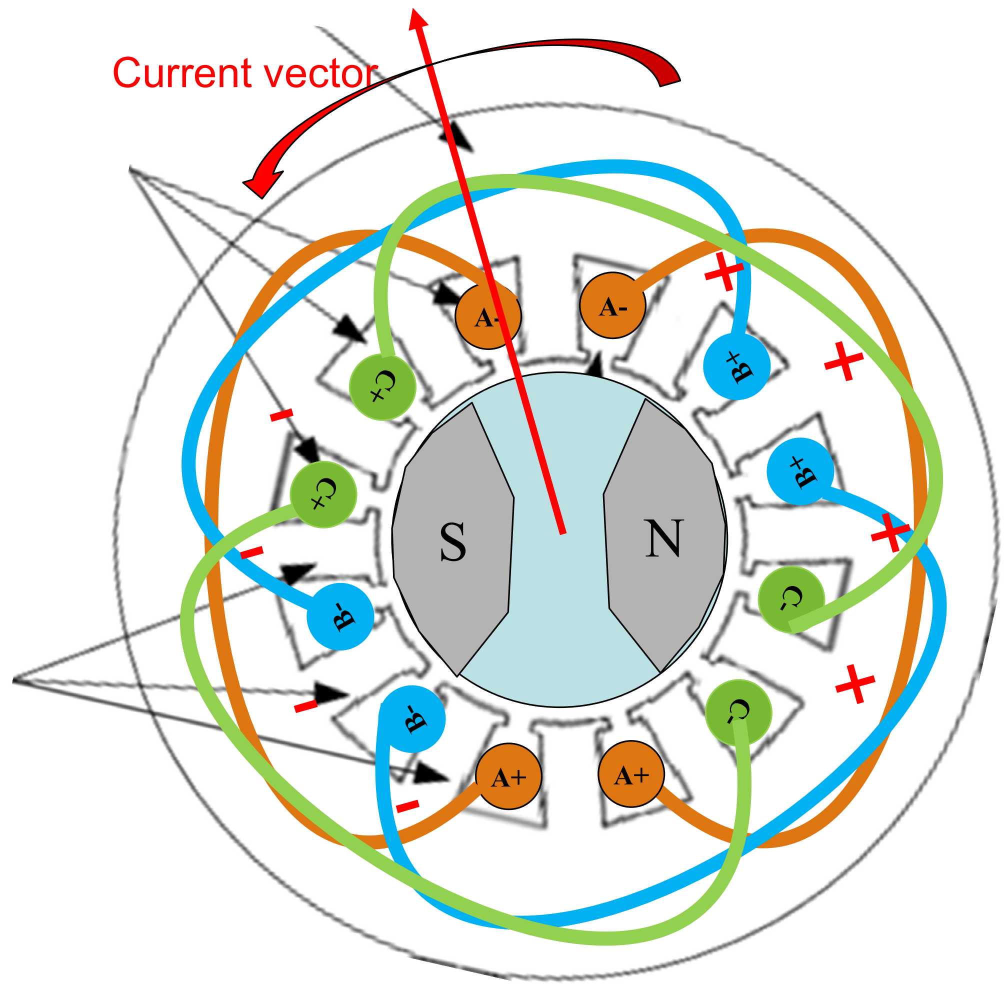
Conclusions

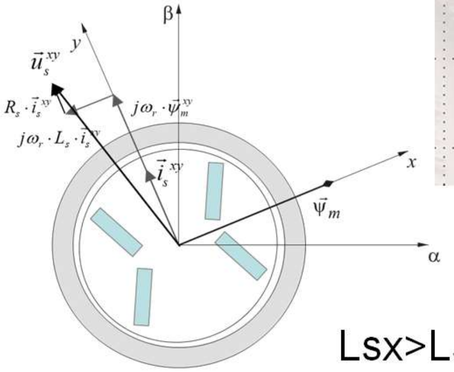
- **A good control system for a PMSM requires:**
  - *A Current Controller, either a PIE + Modulator OR a Tolerance Band controller*
  - *A field weakening controller.*
- **The proposed field weakening controller is an extention of a loss minimisation strategy:**
  - *Set the current references for lowest TOTAL losses (includning resistive, inductive and converter losses)*
  - *When needed, respect the maximum flux limitation and try to keep the torque up.*
  - *Respect also the current limit and reduce torque if needed.*
- **The same data that is the base for control is also useful as base for modelling**




N
S

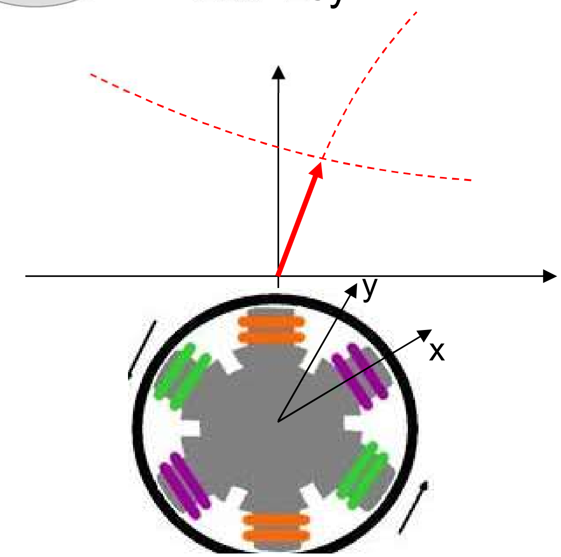



Current vector
A-
A-
B+
B+
C-
C-
A+
A+
B-
B-
C+
C+
S
N

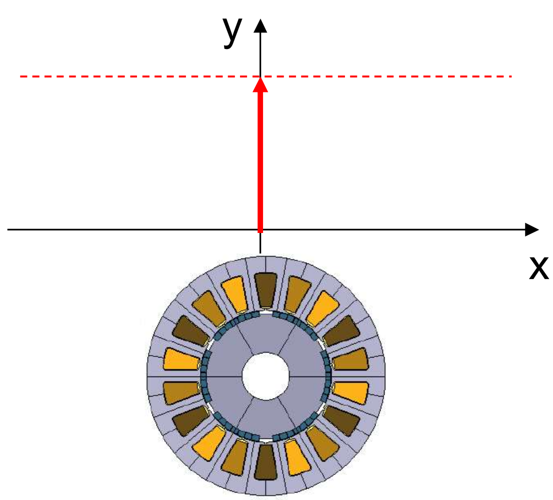


$$= \underbrace{\psi_m \cdot i_{sy}}_{\text{Lorenz torque}} + \underbrace{(L_{sx} - L_{sy}) \cdot i_{sx} \cdot i_{sy}}_{\text{Reluctance torque}}$$

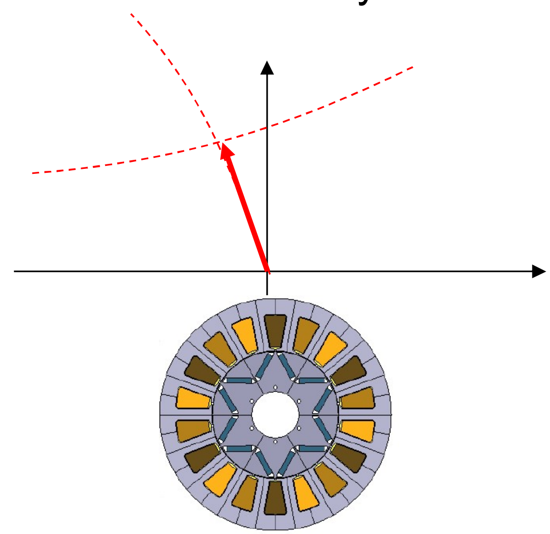
Lsx>Lsy



Lsx=Lsy



Lsx < Lsy



End of the PMSM story