Electric Drives
Laboratory
DII - UniPD

Azionamenti elettrici

Sensorless bassa velocità

Lezioni a.a. 2019-2020

prof. Silverio Bolognani

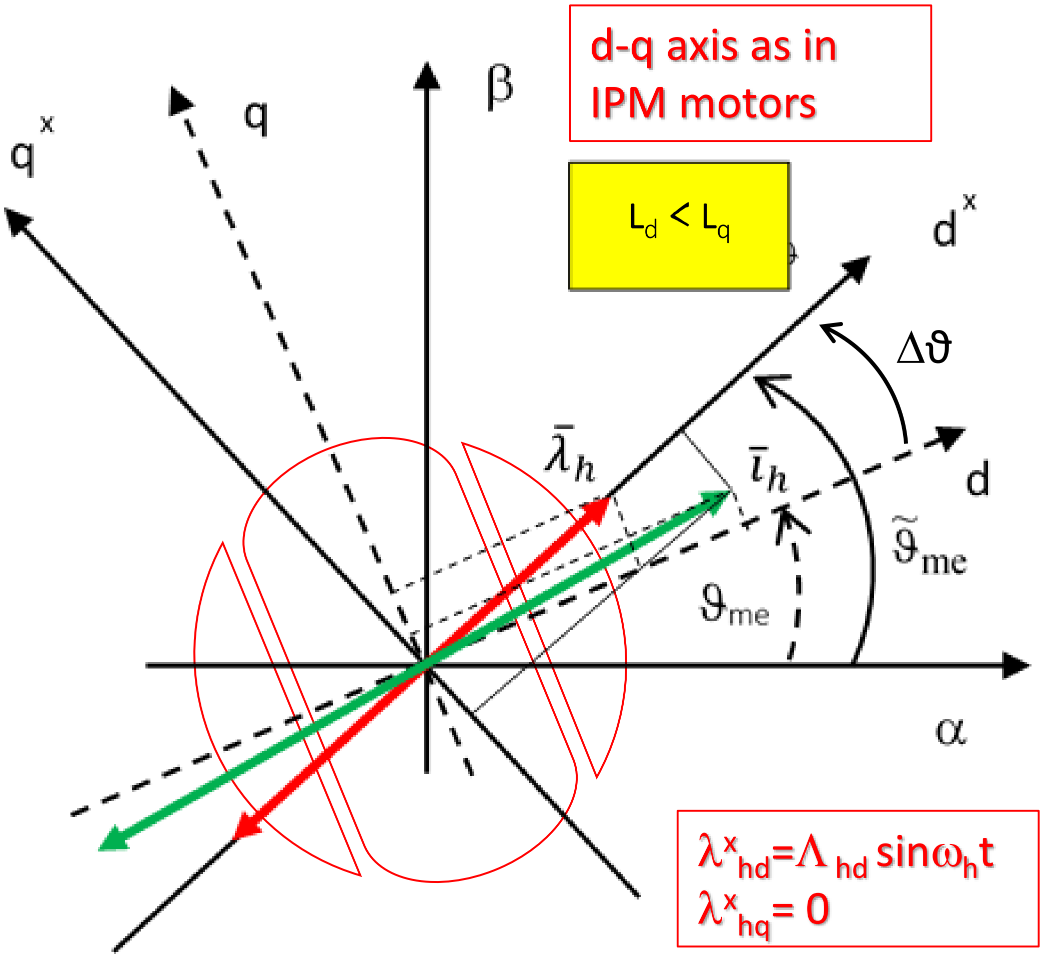
Outline

- 1 - Introduction (ideal motor)
- 2 – Effects of d-q axis cross-coupling
- 3 – Effects of iron saturation
- 4 – Effects of airgap field harmonics
- 5 – Conclusions

1 – Introduction

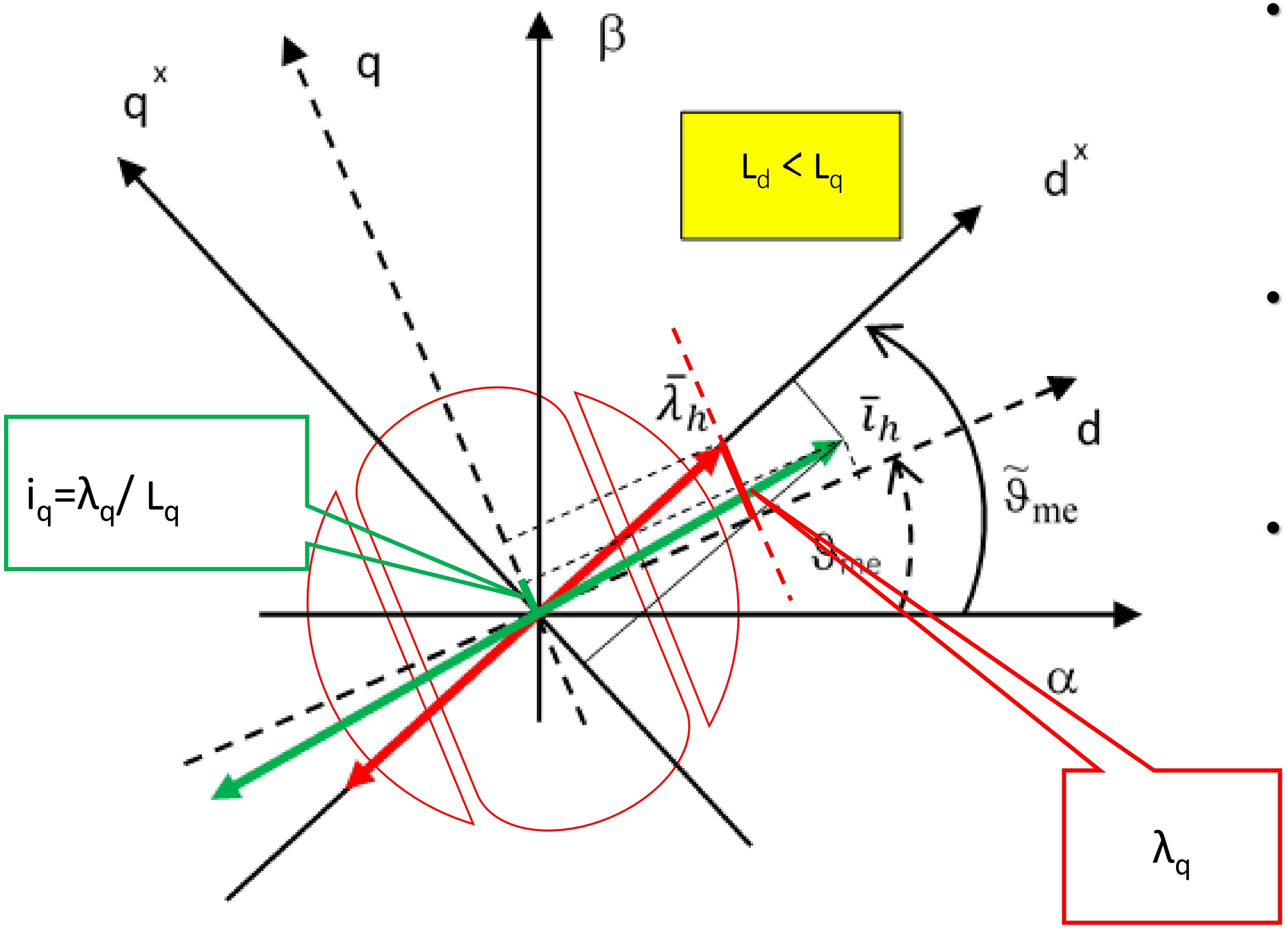
- Assumptions (ideal motor):
  - L_d and L_q are <u>constant</u>
    - no iron saturation (no current dependence)
    - no airgap field harmonics (no rotor position dependence)
  - L_{dq} is <u>zero</u>
    - no d-q axis cross coupling

– L_d and L_q are <u>constant</u> ; L_{dq} is <u>zero</u>



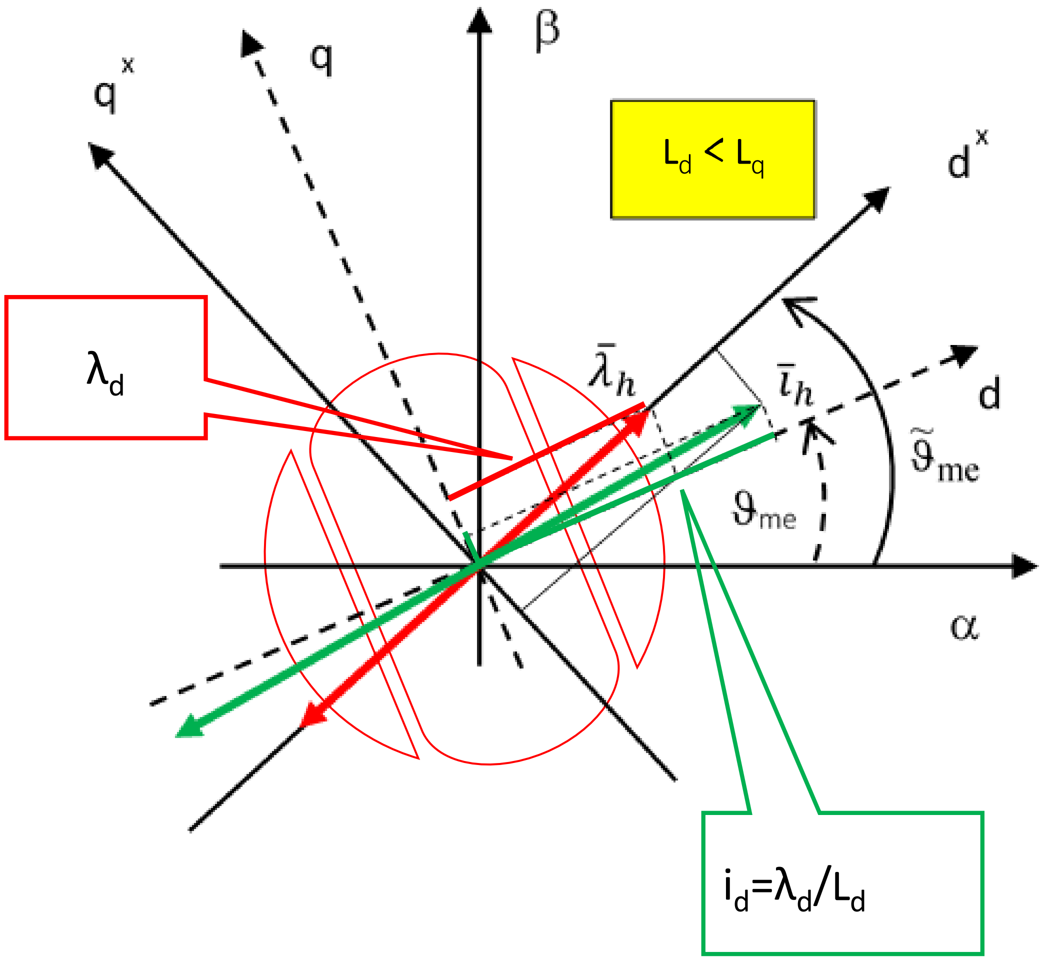
- d-q are the actual axes which position is unknown
- d^x-q^x are the estimated axes which position is estimated
- a hf pulsating flux is injected along d^x (red vector)
- a hf pulsating current occurs not aligned with the flux if there is a position estimation error (green vector)

– L_d and L_q are constant ; L_{dq} is zero



- The pulsating flux has a pulsating q-component (red) (along the actual q- axis)
- This causes a pulsating q-component of the current (green)
- Flux and current are related by the hf q-axis indutance at the operating point

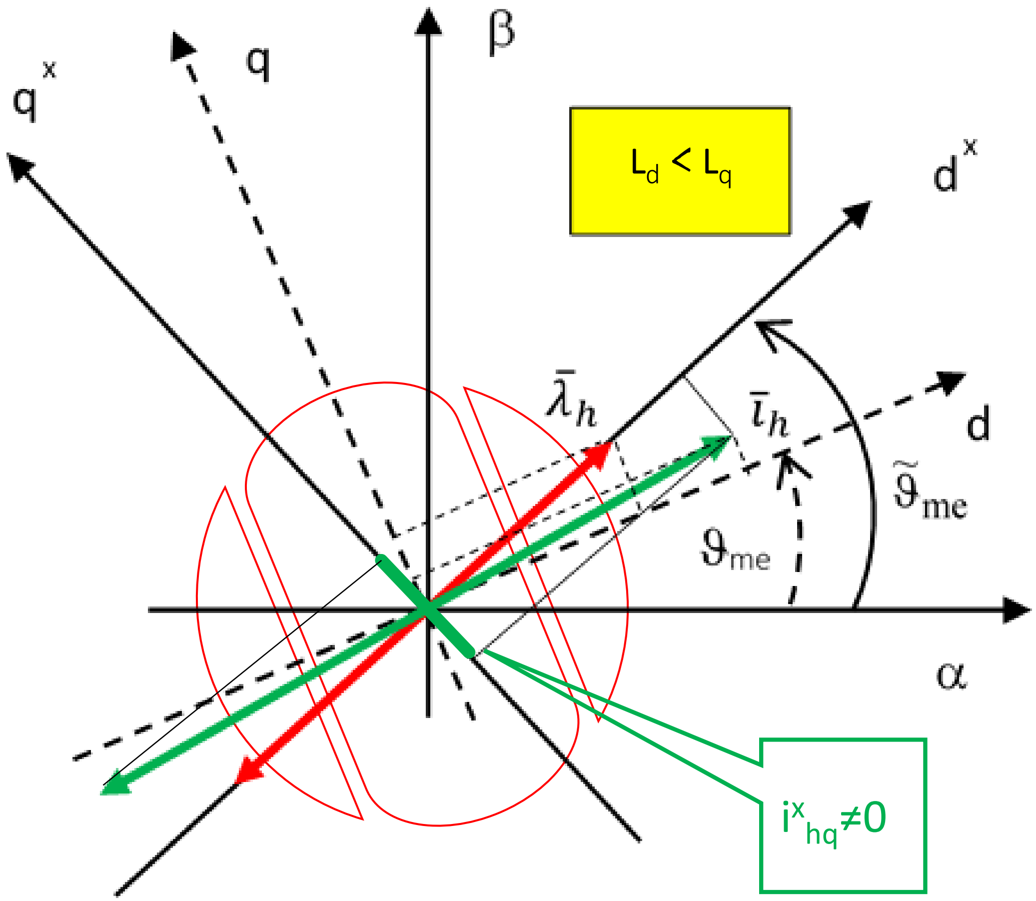
– L_d and L_q are constant ; L_{dq} is zero



- The pulsating flux has also a pulsating d-component (red) (along the actual d- axis)
- This causes a pulsating d-component of the current (green)
- Flux and current are related by the hf d-axis indutance at the operating point
- **If (L_d < L_q) the d-axis current is, proportionally to the flux components, higher than the q-axis one.**

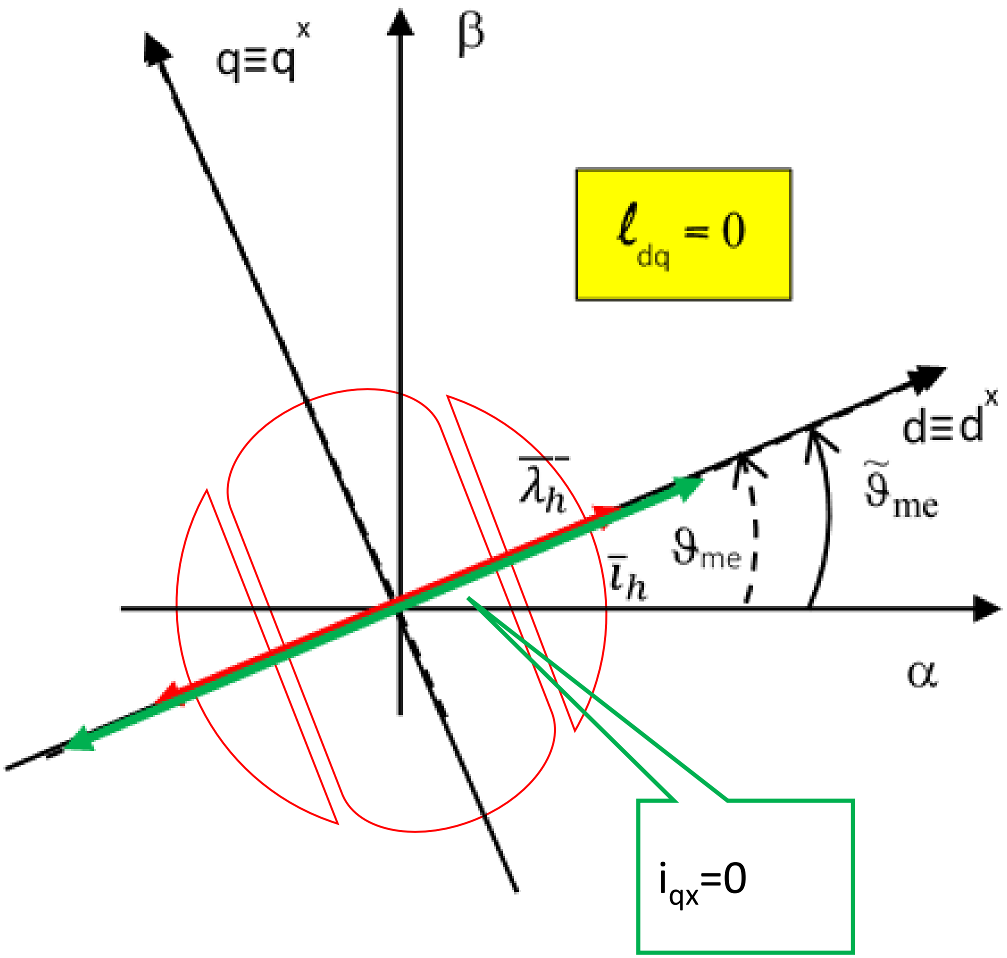
$$\Rightarrow i_d / i_q > \lambda_d / \lambda_q$$

– L_d and L_q are constant ; L_{dq} is zero



- …then the hf current pulses along a direction which is between d^x- and d- axes.
- This is recognized by the presence of a current component along q^x-axis .
- A control mechanism can adjust the estimated position (of d^x) toward the actual one in order to nullify the current i_{qx}.

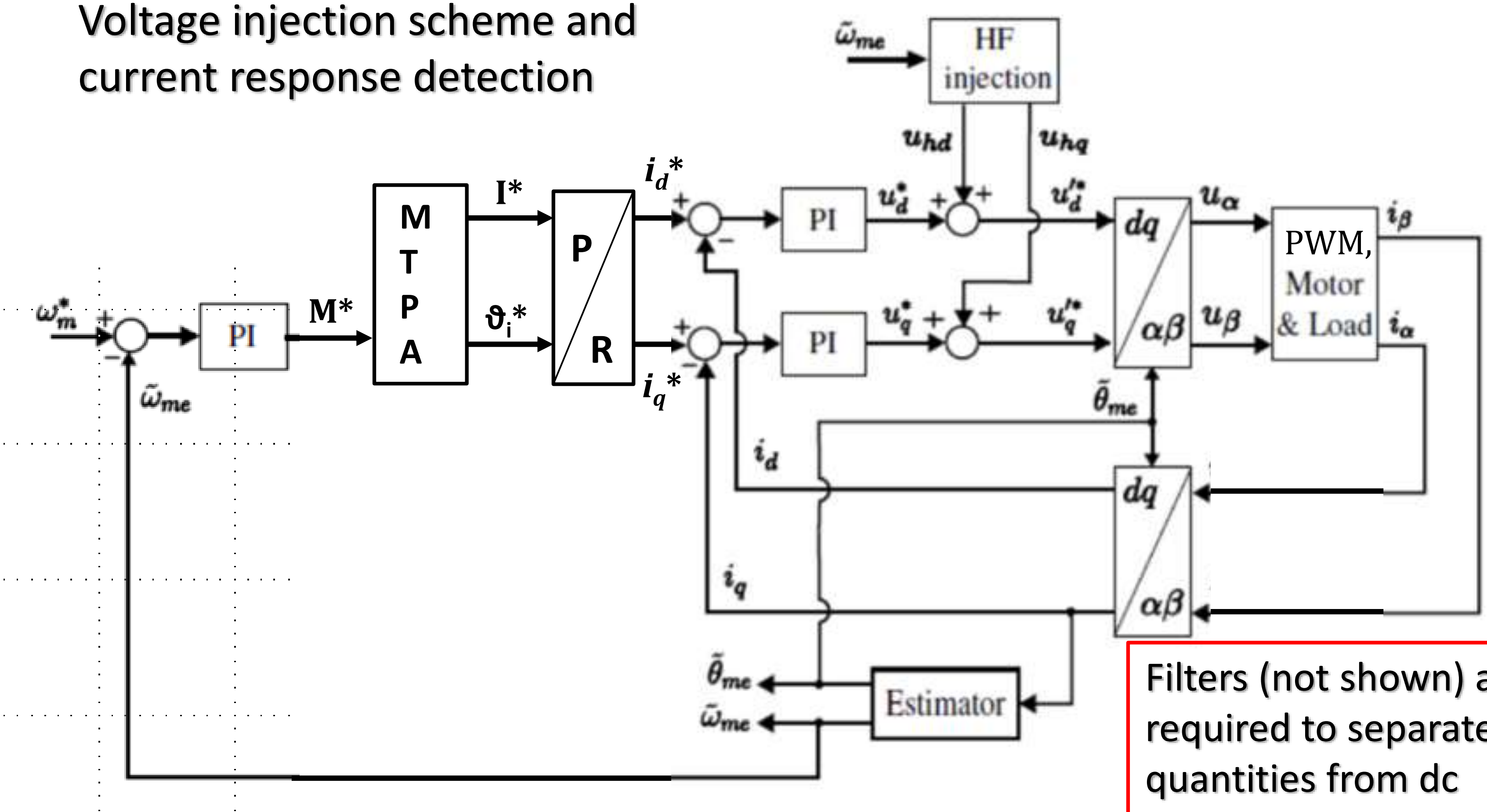
– L_d and L_q are constant ; L_{dq} is zero



- When i_{qx}=0, the directions of d^x- and d-axis coincide, as well as those of the flux and current vectors, because a current along the d-axis produces only a flux along the d-axis ….
- … provided that the mutual inductance L_{dq} be null!

– L_d and L_q are <u>constant</u> ; L_{dq} is <u>zero</u>

Voltage injection scheme and current response detection



Filters (not shown) are required to separate hf quantities from dc quantities

– L_d and L_q are constant ; L_{dq} is zero

Injection of hf voltages in the estimated d^x-q^x axes and flux response

Motor equation

- $$\bar{u}^x = R\bar{\imath}^x + \frac{d\bar{\lambda}^x}{dt} + j\omega_x\bar{\lambda}^x$$

Injected voltages

- $$\begin{aligned} u_{hd}^x &= U_{hd}\cos\omega_h t \\ u_{hq}^x &= U_{hq}\sin\omega_h t \end{aligned}$$

Resulting fluxes

- $$\begin{aligned} \lambda_{hd}^x &= \Lambda_{hd}\sin\omega_h t \\ \lambda_{hq}^x &= \Lambda_{hq}\cos\omega_h t \end{aligned}$$

with

$$\Lambda_{hd} = \frac{U_{hd}\omega_h - U_{hq}\omega_x}{\omega_h^2 - \omega_x^2}$$

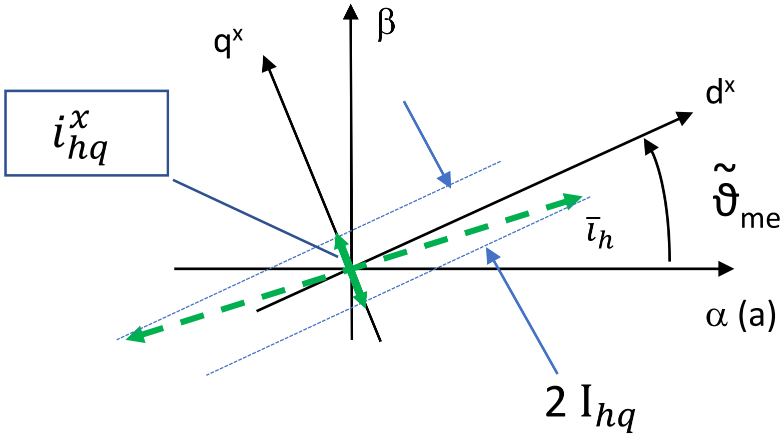
$$\Lambda_{hq} = \frac{U_{hd}\omega_x - U_{hq}\omega_h}{\omega_h^2 - \omega_x^2}$$

Stator resistance voltage drop is neglected

– L_d and L_q are constant ; L_{dq} is zero

Injection of hf voltages for pulsating flux and current response

- Assuming $U_{hq}=U_{hd}\omega_x/\omega_h$ it results



- $$\Lambda_{hd} = \frac{U_{hd}}{\omega_h} \quad \text{and} \quad \Lambda_{hq} = 0$$

- $$i^x_{hd} = \frac{U_{hd}}{\omega_h L_d L_q}(L_\Sigma + L_\Delta cos2\Delta\vartheta)\sin\omega_h t = I_{hd}\sin\omega_h t$$
$$i^x_{hq} = \frac{-U_{hd}}{\omega_h L_d L_q}(L_\Delta sin2\Delta\vartheta)\sin\omega_h t = I_{hq}\sin\omega_h t$$

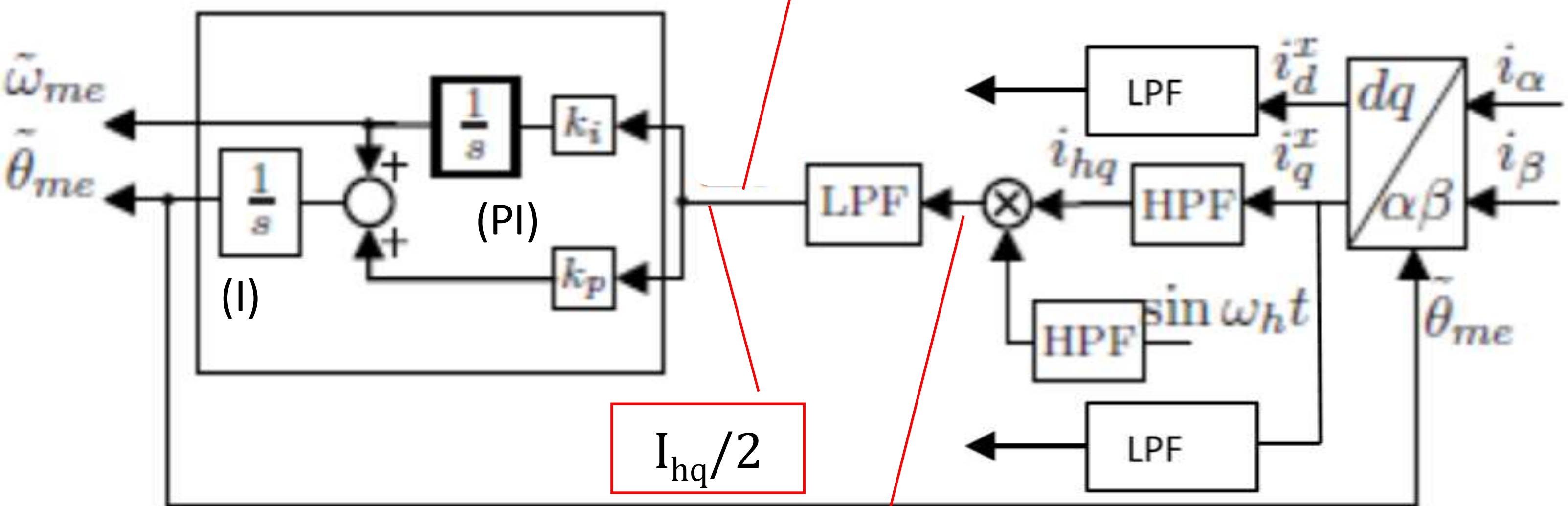
with $L_\Delta = (L_q - L_d)/2$

– L_d and L_q are constant ; L_{dq} is zero

Demodulation (hf current detection) and speed/position observer

Positive I_{hq} increases estimated speed and thus $\Delta\vartheta$ and viceversa

This is forced to zero by PI action

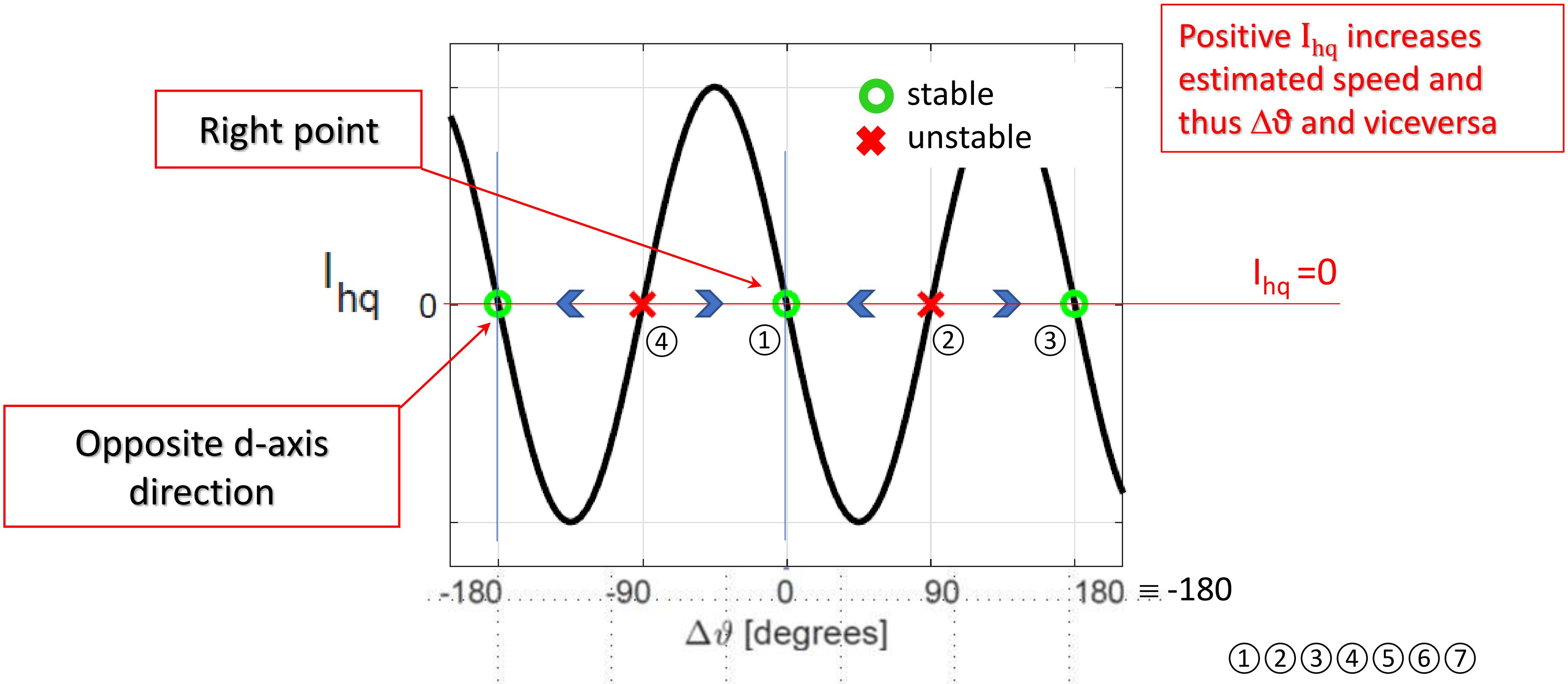


$I_{hq}/2$

$$I_{hq}\sin^2\omega_h t = I_{hq}/2 - I_{hq}/2\cos 2\omega_h t$$

– L_d and L_q are <u>constant</u> ; L_{dq} is <u>zero</u>

Observer convergence in the I_{hq} - $\Delta\vartheta$ plane (I_{hq}=0 $\Rightarrow (L_\Delta sin2\Delta\vartheta)$=0)



2 – Effects of d-q axis cross-coupling

- Assumptions:
  - L_d and L_q are constant
    - no iron saturation (no current dependence)
    - no airgap field harmonics (no rotor position dependence)
  - ~~L_{dq} is zero~~ Ldq is constant ≠ 0
    - ~~no d-q axis cross coupling~~

– L_d and L_q are constant ; L_{dq} is constant ≠ 0

Current response and estimation error equations

$$I_{hq} = \frac{U_h}{2\omega_h(L_d L_q - L_{dq}^2)}(-L_\Delta sin2\Delta\theta - L_{dq}cos2\Delta\theta)$$

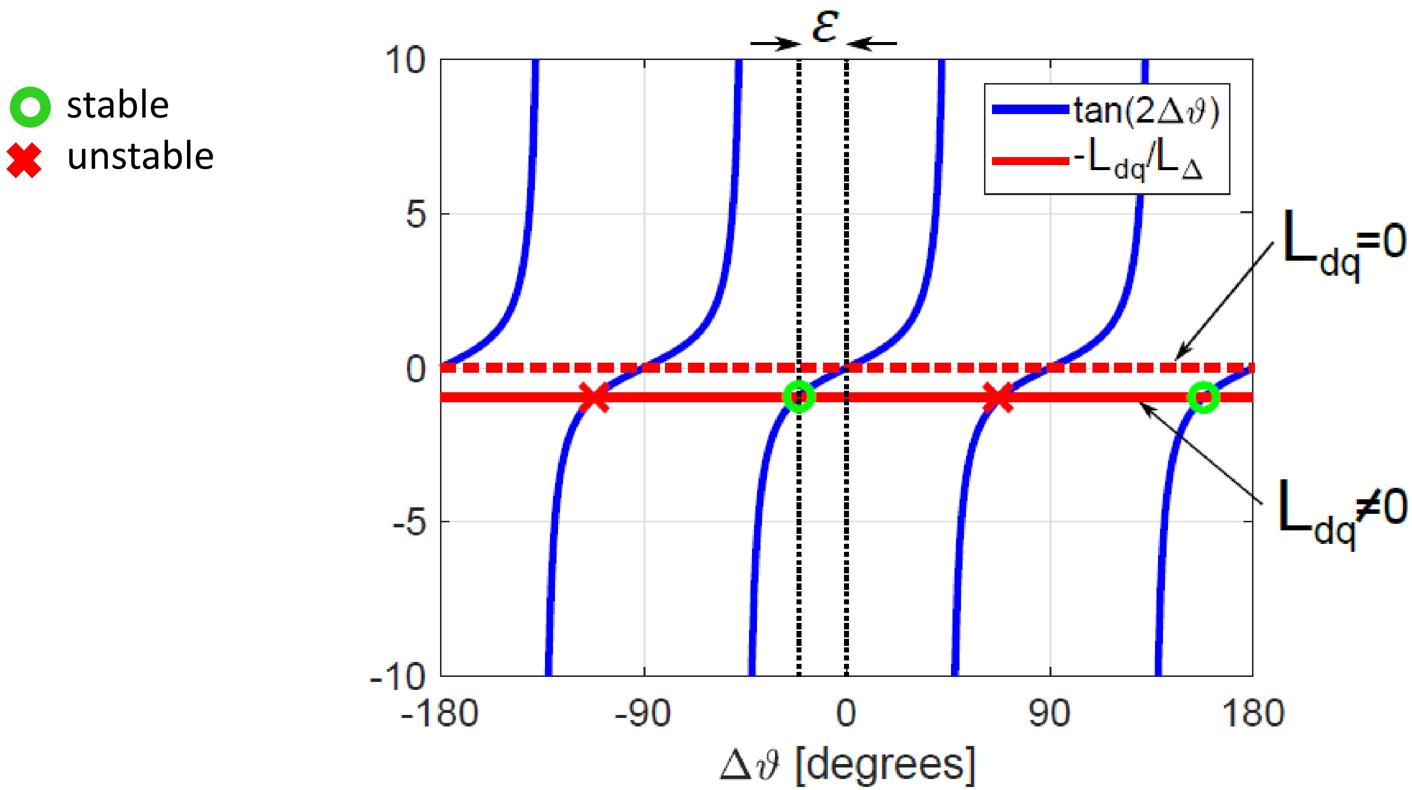
$$I_{hq} \rightarrow 0 \quad \Rightarrow \quad tan(2\Delta\theta) = \frac{-L_{dq}}{L_\Delta}$$

$$\Rightarrow \quad \varepsilon = \Delta\theta = \frac{1}{2} arctan\left(\frac{-L_{dq}}{L_\Delta}\right)$$

L_{dq} should be as small as possible for accuracy reasons.

– L_d and L_q are constant ; L_{dq} is constant ≠ 0

Observer convergence plot (I_{hq}=0 $\Rightarrow tan(2\Delta\theta) = \frac{-L_{dq}}{L_\Delta}$)

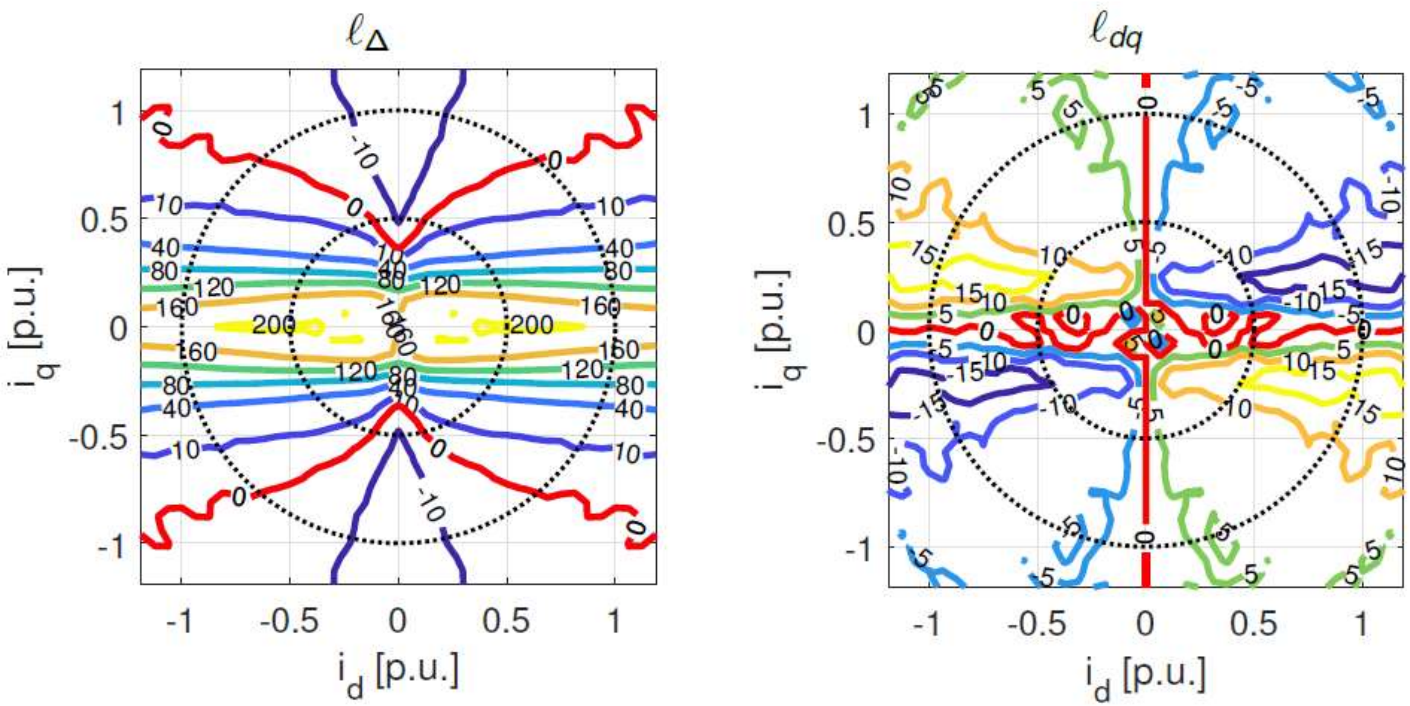


3 – Effects of iron saturation

- Assumptions:
  - L_d and L_q are constant
    (no iron saturation, no rotor position dependence)
- >>> $\ell_d = \ell_d(i_d,i_q)$, $\ell_q = \ell_q(i_d,i_q)$ (differential)
  - L_{dq} is zero L_{dq} is constant ≠ 0
- >>> $\ell_{dq} = \ell_{dq}(i_d,i_q) \neq 0$ (differential)

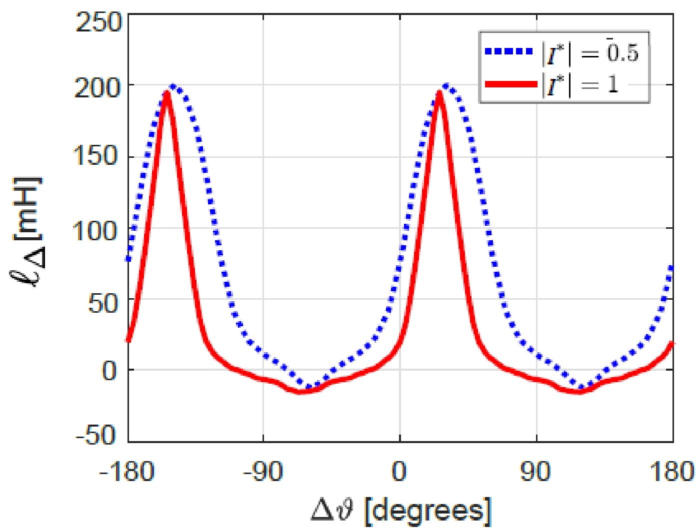
-- $\ell_d = \ell_d(i_d, i_q)$, $\ell_q = \ell_q(i_d, i_q)$, $\ell_{dq} = \ell_{dq}(i_d, i_q)$

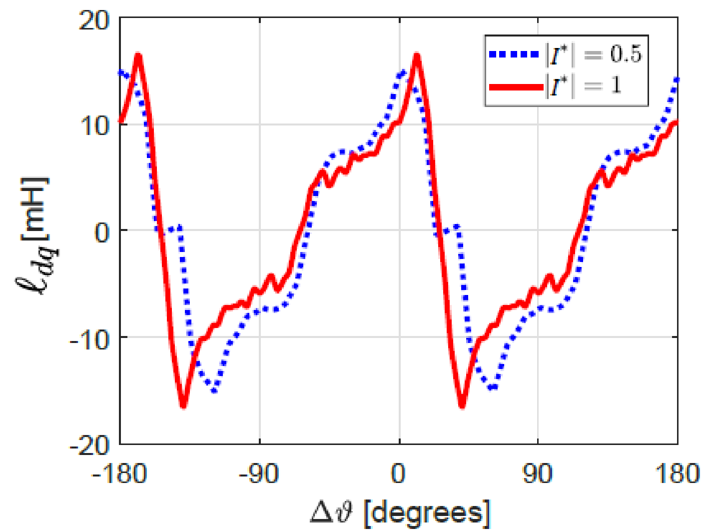
Measured Inductance maps of a SyRM



-- $\ell_d = \ell_d(i_d, i_q), \quad \ell_q = \ell_q(i_d, i_q), \quad \ell_{dq} = \ell_{dq}(i_d, i_q)$

Measured Inductance along I*=0.5 and I*=1 (angle measured from MTPA)





-- $\ell_d = \ell_d(i_d, i_q), \quad \ell_q = \ell_q(i_d, i_q), \quad \ell_{dq} = \ell_{dq}(i_d, i_q)$

Current response equation in presence of iron saturation

$$I_{hq} = \frac{U_h}{\omega_h(\ell_{dq}^2(i_d, i_q) - \ell_d(i_d, i_q)\ell_q(i_d, i_q))}[\ell_\Delta(i_d, i_q)\sin(2\Delta\vartheta) + \ell_{dq}(i_d, i_q)\cos(2\Delta\vartheta)]$$

In case of sensorless drive:

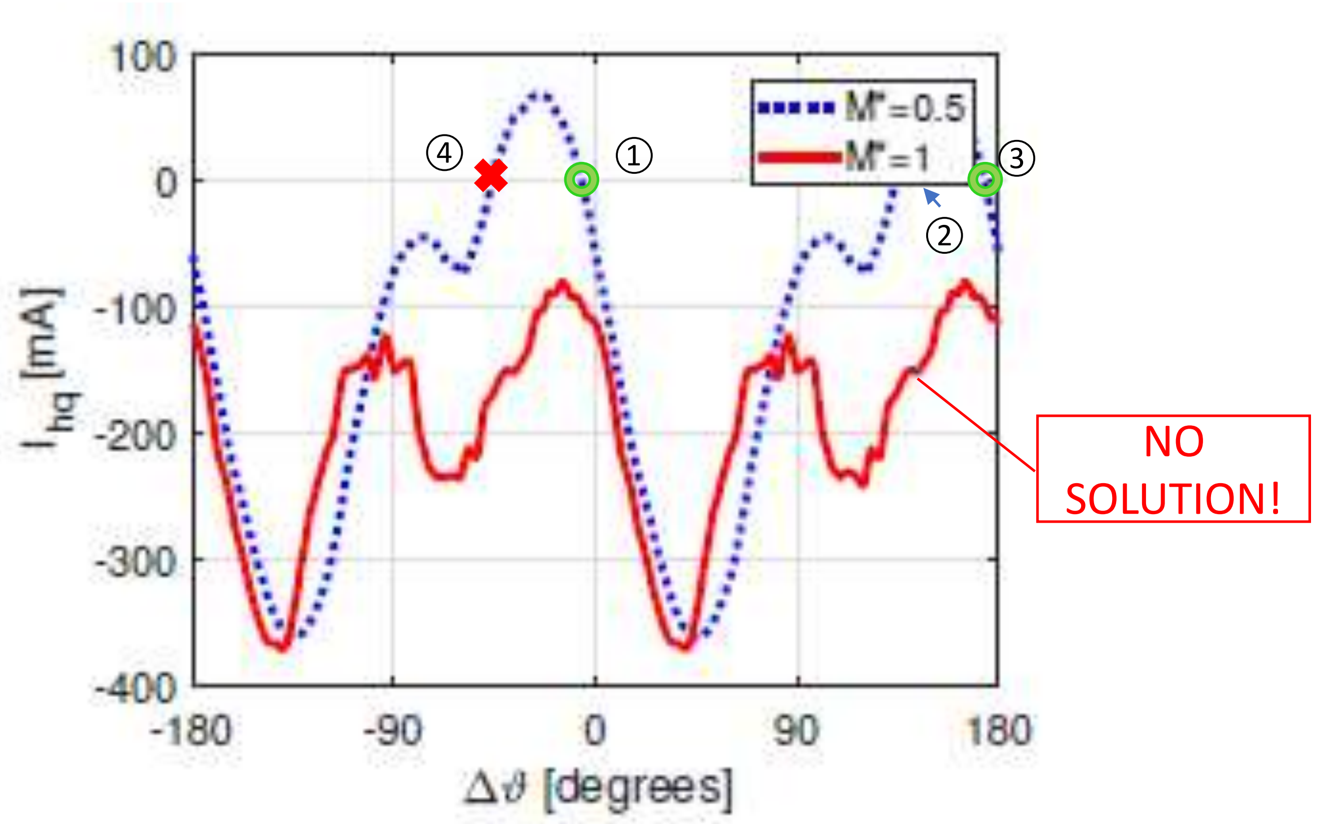
$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos(\Delta\vartheta) & -\sin(\Delta\vartheta) \\ \sin(\Delta\vartheta) & \cos(\Delta\vartheta) \end{bmatrix} \begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} = \begin{bmatrix} f(\bar{i^*}, \Delta\vartheta) \\ g(\bar{i^*}, \Delta\vartheta) \end{bmatrix}$$

$$I_{hq}(\bar{i^*}, \Delta\vartheta) = \frac{U_h}{\omega_h(\ell_{dq}^2(\bar{i^*}, \Delta\vartheta) - \ell_d(\bar{i^*}, \Delta\vartheta)\ell_q(\bar{i^*}, \Delta\vartheta))}[\ell_\Delta(\bar{i^*}, \Delta\vartheta)\sin(2\Delta\vartheta) + \ell_{dq}(\bar{i^*}, \Delta\vartheta)\cos(2\Delta\vartheta)]$$

$$I_{hq} \rightarrow 0 \quad \Rightarrow \quad \tan(2\Delta\vartheta) = -\frac{\ell_{dq}(|i^*|, \Delta\vartheta)}{\ell_\Delta(\|i^*|, \Delta\vartheta)}$$

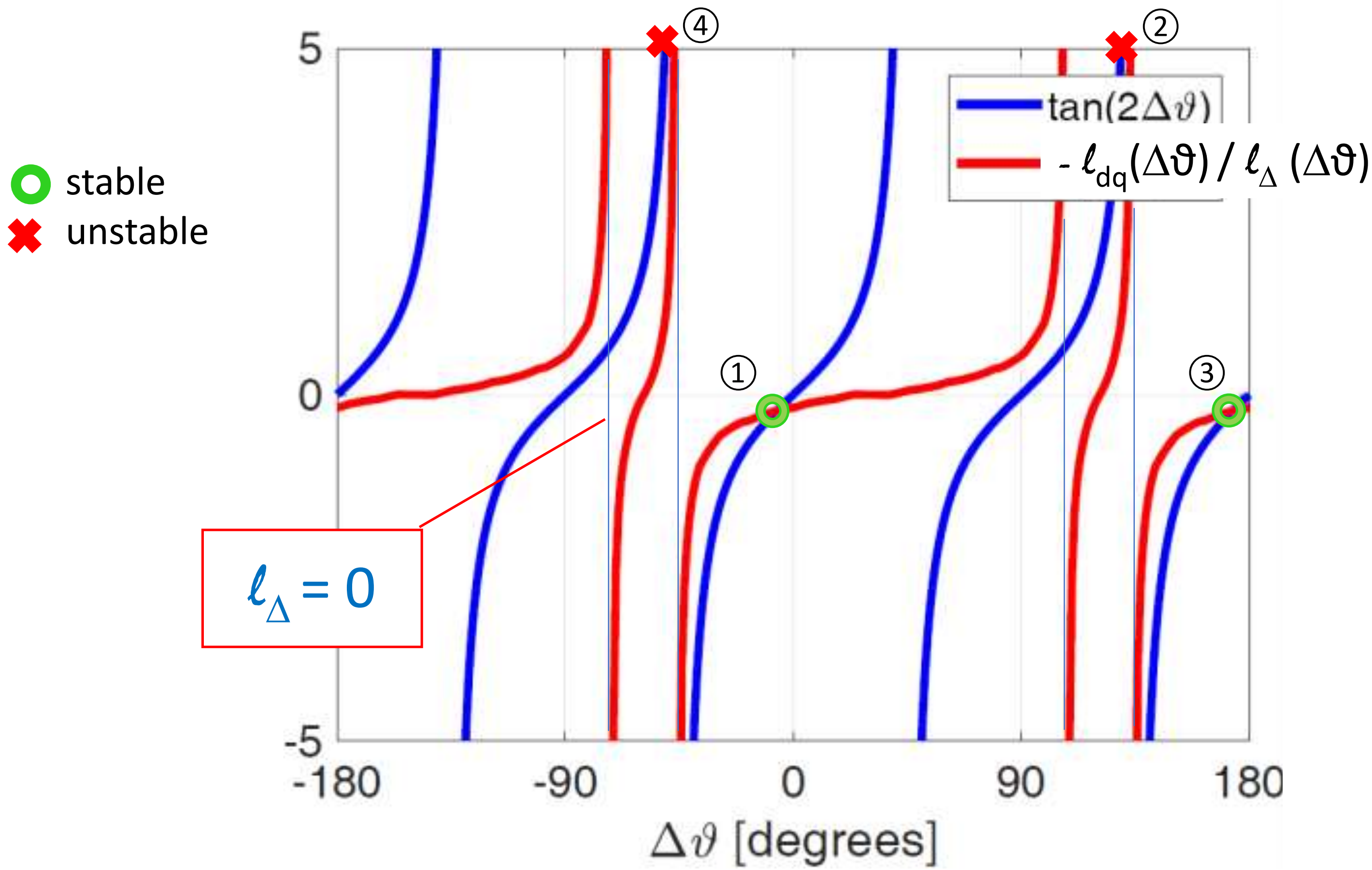
-- $\ell_d = \ell_d(i_d, i_q), \quad \ell_q = \ell_q(i_d, i_q), \quad \ell_{dq} = \ell_{dq}(i_d, i_q)$

Observer convergence in the I_{hq} - $\Delta\vartheta$ plane (I_{hq}=0)



-- $\ell_d = \ell_d(i_d, i_q)$, $\ell_q = \ell_q(i_d, i_q)$, $\ell_{dq} = \ell_{dq}(i_d, i_q)$

Observer convergence points (I_{hq}=0) for M*=0.5



-- $\ell_d = \ell_d(i_d, i_q)$, $\ell_q = \ell_q(i_d, i_q)$, $\ell_{dq} = \ell_{dq}(i_d, i_q)$

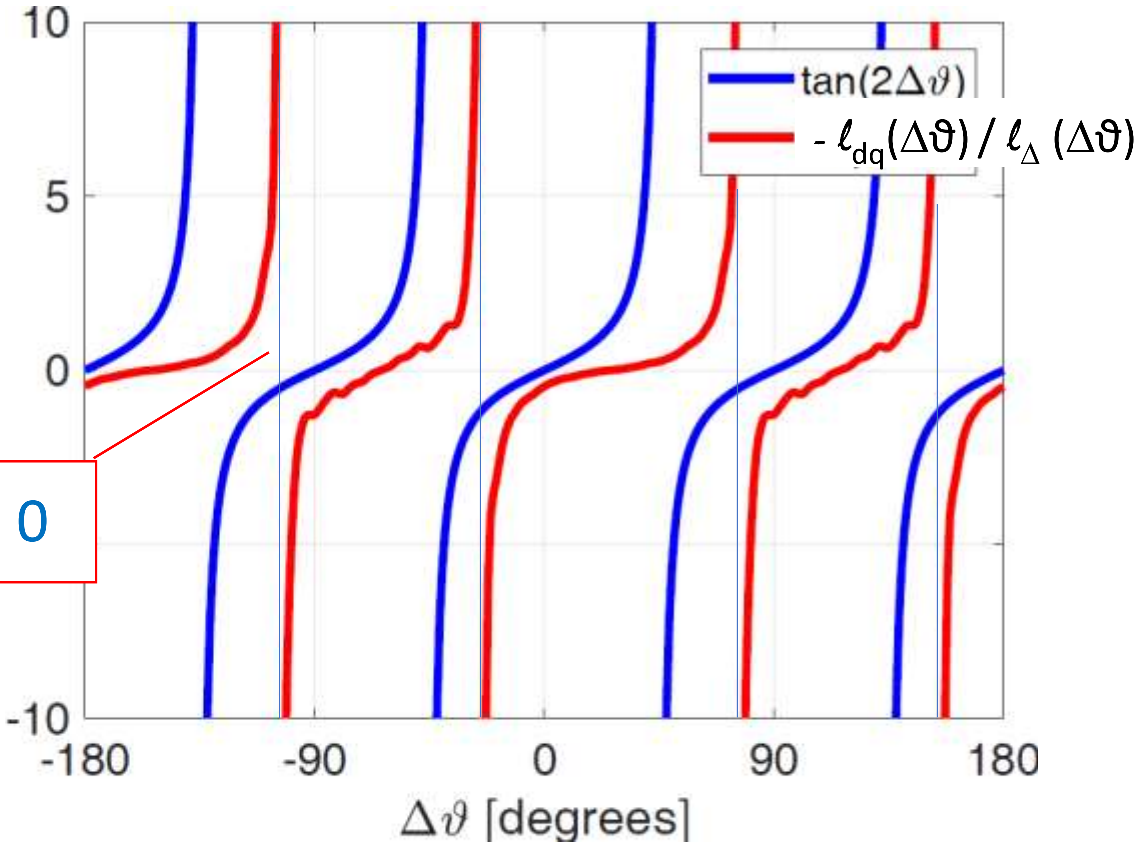
Observer convergence points (I_{hq}=0) for M*=1.0 NO SOLUTION!

Equation

$$\tan(2\Delta\vartheta) = -\frac{\ell_{dq}(|i^*|, \Delta\vartheta)}{\ell_\Delta(\||i^*|, \Delta\vartheta)}$$

has not solutions

$\ell_\Delta = 0$



-- $\ell_d = \ell_d(i_d, i_q), \quad \ell_q = \ell_q(i_d, i_q), \quad \ell_{dq} = \ell_{dq}(i_d, i_q)$

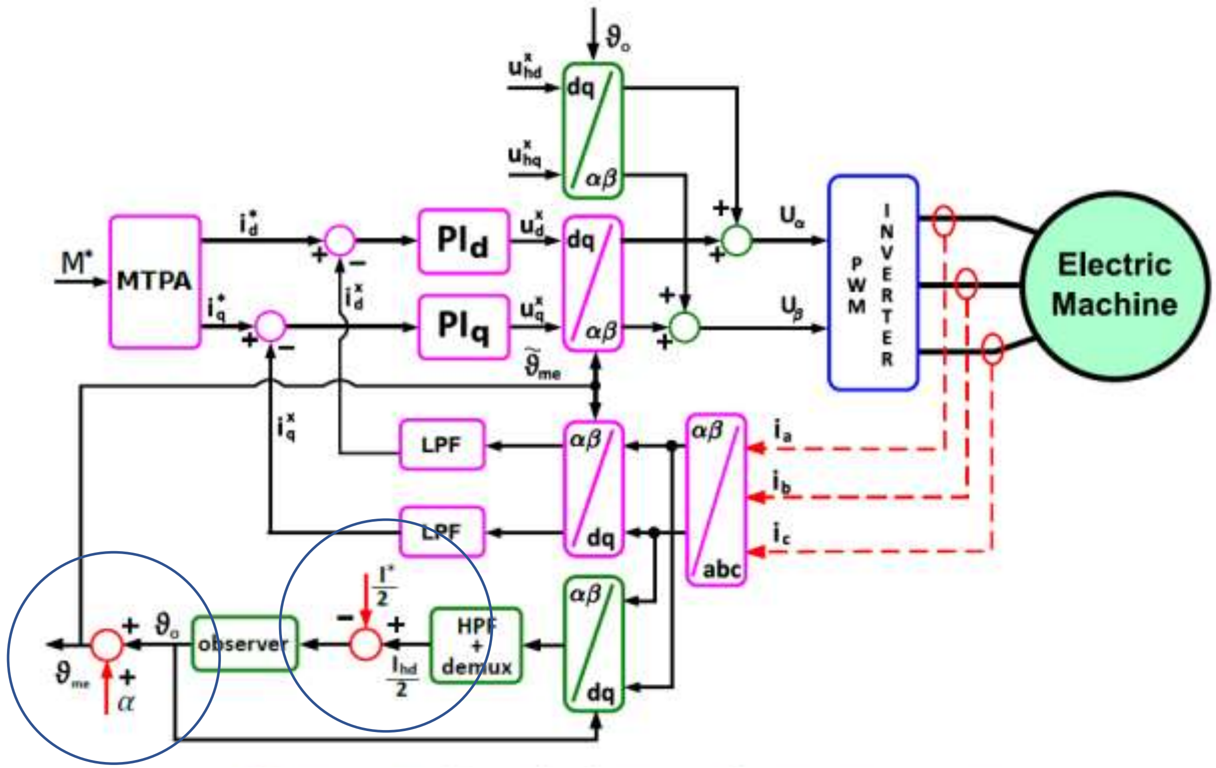
- Compensation: two types of compensation can be incorporated for
  - achieving convergence at any torque level
  - increasing stability margin
  - increasing accuracy

- Angle compensation

- Current compensation

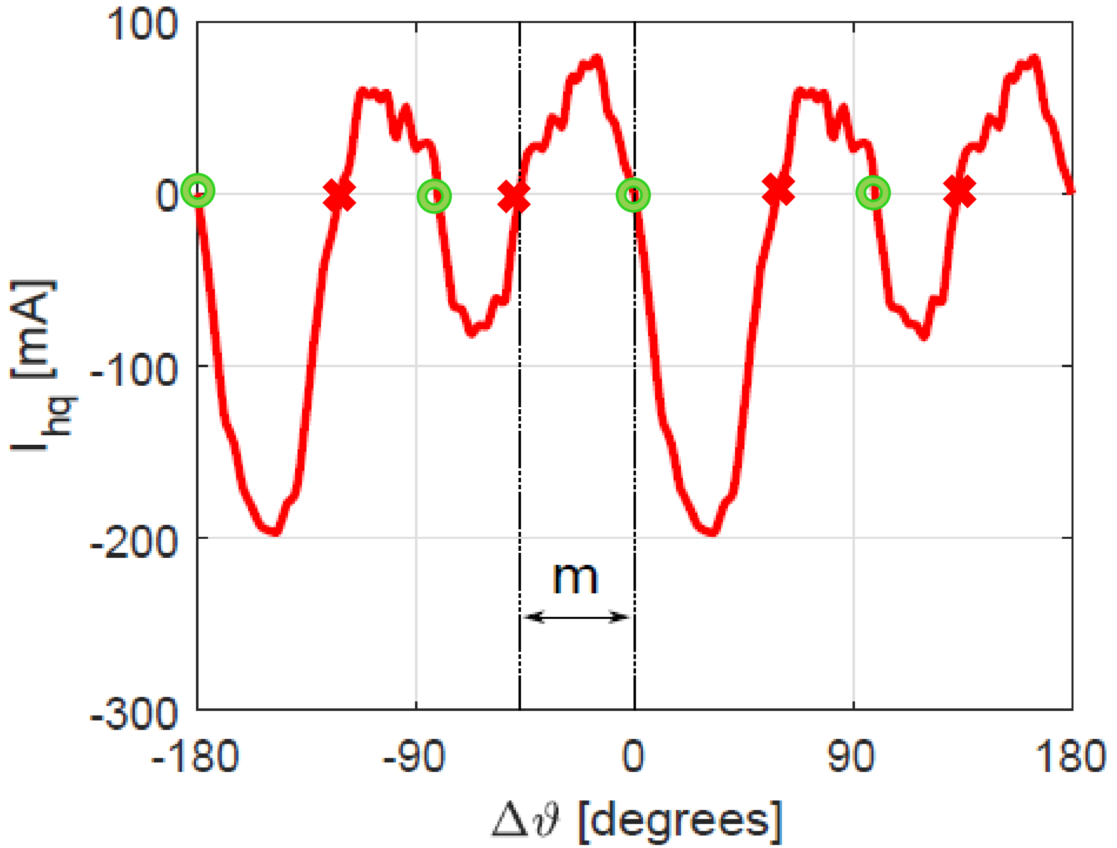
-- $\ell_d = \ell_d(i_d, i_q), \quad \ell_q = \ell_q(i_d, i_q), \quad \ell_{dq} = \ell_{dq}(i_d, i_q)$

- Scheme with Angle and Current compenstion



-- $\ell_d = \ell_d(i_d, i_q), \quad \ell_q = \ell_q(i_d, i_q), \quad \ell_{dq} = \ell_{dq}(i_d, i_q)$

Observer convergence points (I_{hq}=0) with both compensations and for M* = 1: *margin* is large



There should be more that two stable convergence points!

4 – Effects of airgap field harmonics

- Assumptions:
  - L_d and L_q are <u>constant</u> with the current but varying with rotor position
  - (no iron saturation, no rotor position dependence)
- >>> $L_d = L_d(\vartheta_{me}), L_q = L_q(\vartheta_{me})$
  - L_{dq} is zero L_{dq} <u>constant with the current</u> but varying with rotor position
- >>> $L_{dq} = Ldq(\vartheta me) \neq 0$

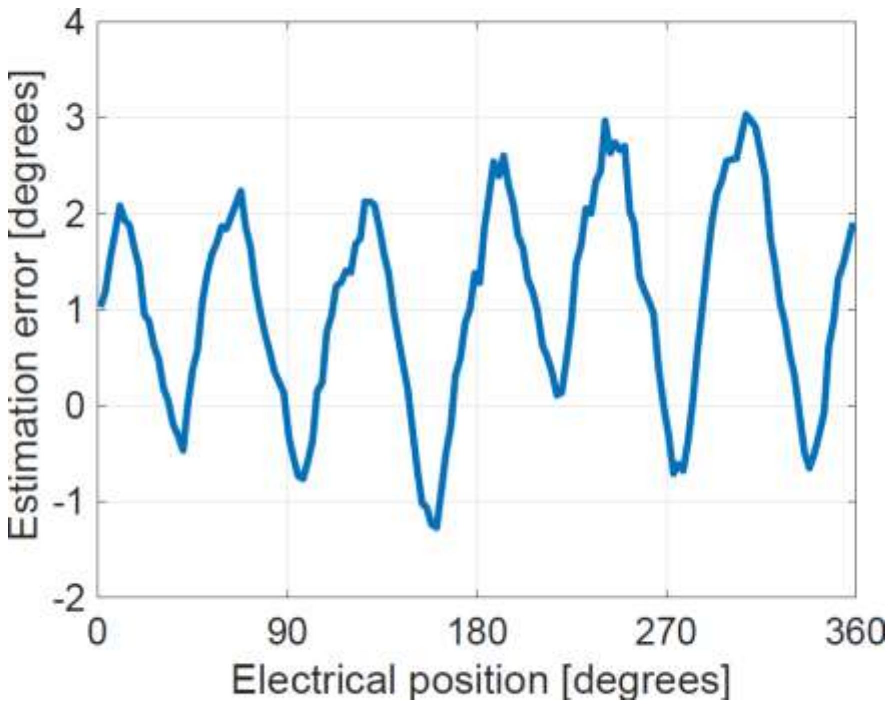
-- $L_d = L_d(\vartheta_{me})$, $L_q = L_q(\vartheta_{me})$, $L_{dq} = L_{dq}(\vartheta_{me})$

- In case of **airgap field harmonics** (due to winding distribution (an example is the fractional-slot winding))
  - d and q self inductances vary with the rotor position
  - d-q cross inductance appears (even if iron saturation is not present), variable with the rotor position and with null average value. Then

$$\varepsilon = \Delta\theta = \frac{1}{2}\, arctan\left(\frac{-L_{dq}(\vartheta_{me})}{L_{\Delta}(\vartheta_{me})}\right)$$

-- $L_d = L_d(\vartheta_{me})$, $L_q = L_q(\vartheta_{me})$, $L_{dq} = L_{dq}(\vartheta_{me})$

Measured estimation error in presence of airgap field harmonics and fixed angle and current compensation. *Light iron saturation is also present*.



The maps previously shown are changing with the rotor position in periodical manner

5 - Conclusions

- Self-sensing capability of Synchronous Motors (by pulsating hf flux injection) is affected by iron saturation and air-gap field harmonics

- Self-sensing capability is difficult in high torque operation.

- Some «compensations» can be introduced for improving perfomance and accuracy.

<u>Next future EDLab activities</u>

- Rotating hf flux injection exhibits similar limits and troubles, but has additional features.

- Overall perfomance can be improved by a proper design of the motor.