Sensorless control of synchronous machines with high frequency voltage injection

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Outline

- **Reluctance machine** review
- Introduction: key concepts of **sensorless operation**
- **Convergence** of **HF** voltage **injection**:
  - **ideal case**: no iron saturation, no cross-saturation $\lambda_d = L_d i_d$, $\lambda_q = L_q i_q$
  - constant inductances **with cross-coupling** $\lambda_d = L_d i_d + L_{dq} i_q$, $\lambda_q = L_{dq} i_d + L_q i_q$
  - **real case**: with iron saturation with cross-saturation $\lambda_d = \lambda_d(i_d, i_q)$, $\lambda_q = \lambda_q(i_d, i_q)$
- **Convergence** range **extension**

Introduction
HF Voltage Injection
Convergence range extension

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Reluctance machine review

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For the sake of simplicity the **reluctance machine** can be considered as an **IPM machine without permanent magnets**.

- Electrical balance of the machine

$$\begin{cases} u_d &= Ri_d + \frac{d\lambda_d}{dt} - \omega_{me}\lambda_q \\ u_q &= Ri_q + \frac{d\lambda_q}{dt} + \omega_{me}\lambda_d \end{cases}$$

- Flux/current relationship

$$\begin{cases} \lambda_d &= L_d i_d \\ \lambda_q &= L_q i_q \end{cases}$$

- Torque equation

$$M = \frac{3}{2}p(\lambda_d i_q - \lambda_q i_d) = \frac{3}{2}p(L_d - L_q) i_d i_q$$

In this lecture the **reluctance machine** is used as a **case study**.

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Introduction: Sensorless Drives

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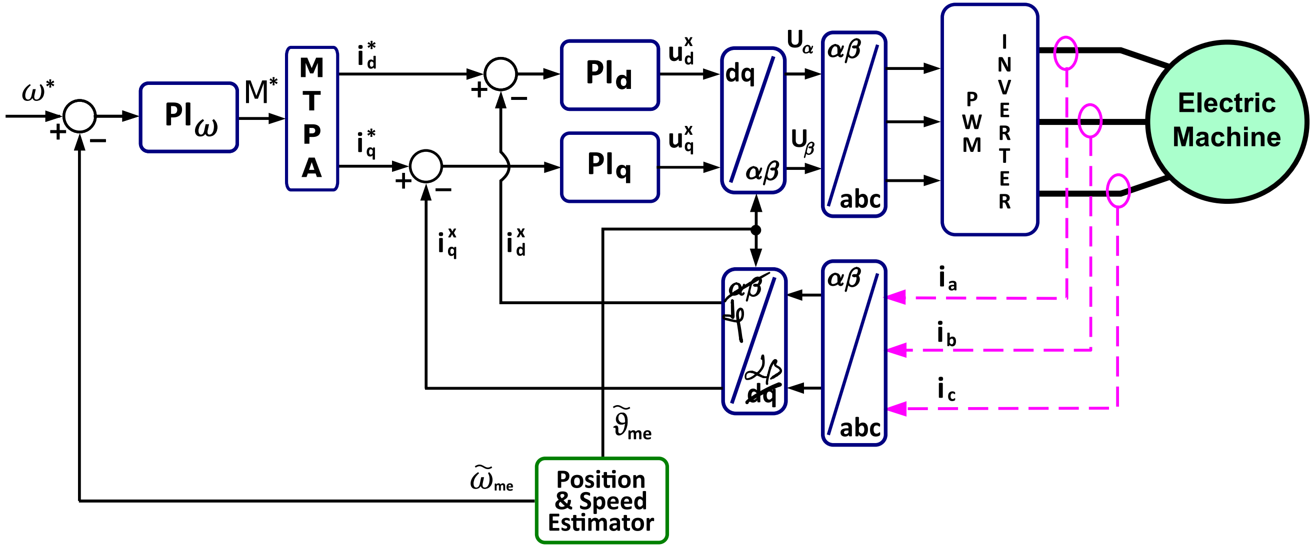
Sensorless drive scheme

General scheme –> it does **not depend** on the **estimation algorithm**.



- The **speed loop** is **neglected** and it is assumed that the d and q current references are given.
- **Current** control **loops** are considered at **steady state** with **no error**

$$i_d^x = i_d^* \quad \text{and} \quad i_q^x = i_q^*$$

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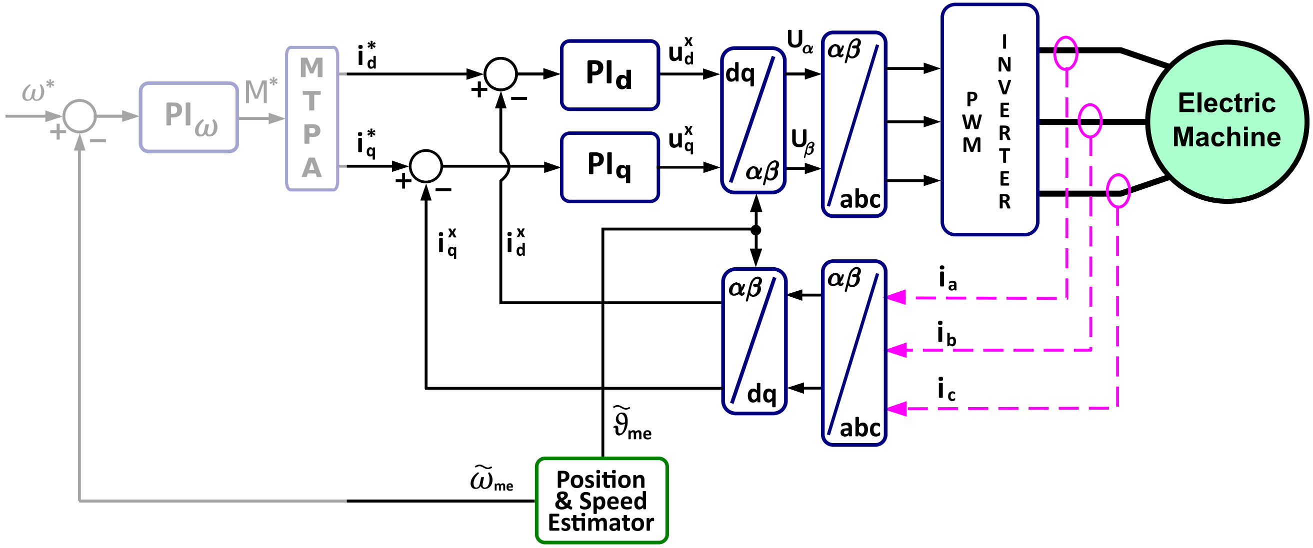

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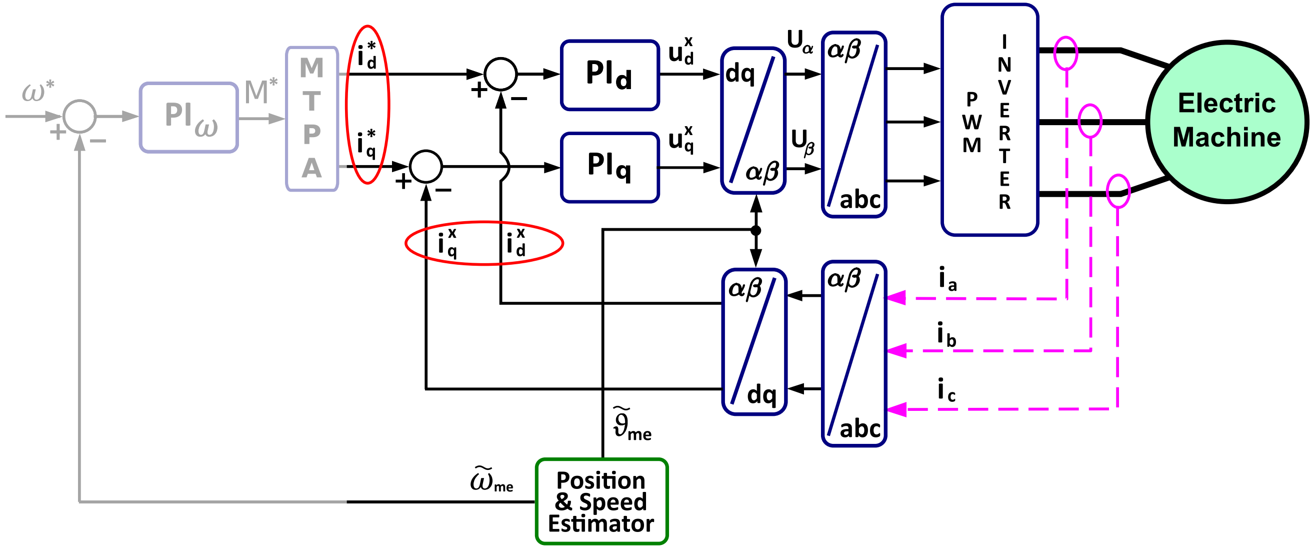

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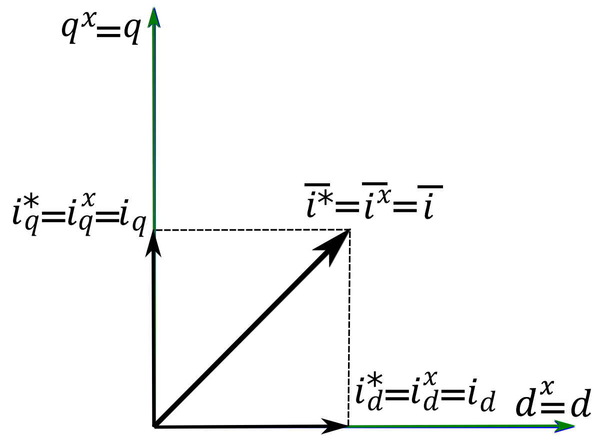
Sensorless operation

Correct estimation $\Delta\vartheta = 0$



- The **estimated**, $d^x q^x$, and **actual**, dq, **axis coincide**.
- The **actual current vector** applied to the machine is the **desired one**
$$\bar{i}^x = \bar{i}^*$$

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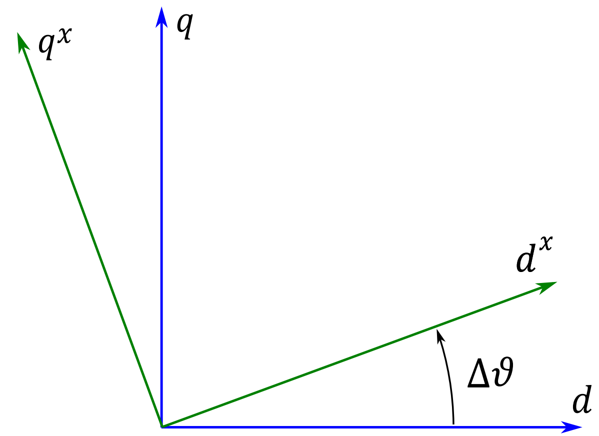
Sensorless operation

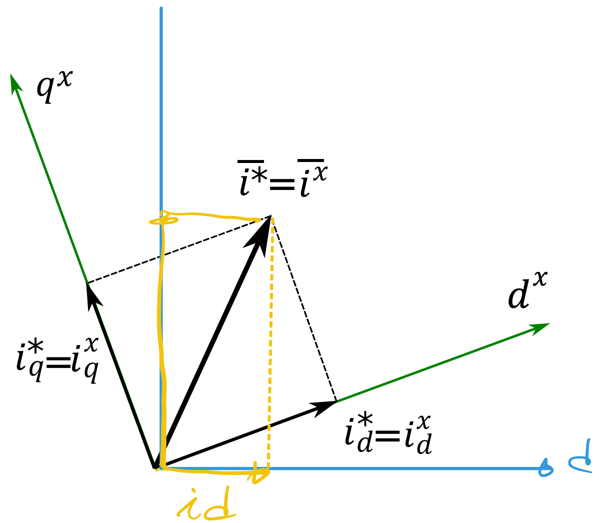
With estimation error $\Delta\vartheta \neq 0$



- With an estimation error the **reference frames are different**.
- The control is **based only on** the estimated position ϑ_{me}^x and thus on the **estimated axis** $d^x q^x$.

Sensorless operation

With estimation error $\Delta\vartheta \neq 0$



- The **currents** in the **estimated** reference **frame** are **controlled to their references**

$$i_d^x = i_d^* \qquad \text{and} \qquad i_q^x = i_q^*$$

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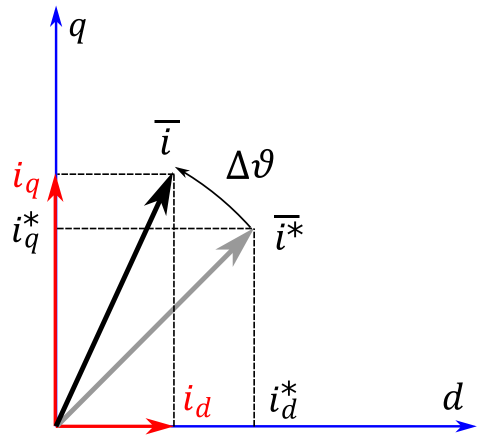
Sensorless operation

With estimation error $\Delta\vartheta \neq 0$



- However, in the actual reference frame the **current vector** is **different from** the **desired one**

$$i_d \neq i_d^* \qquad \text{and} \qquad i_q \neq i_q^*$$

- As the estimation error $\Delta\vartheta$ increases the **working point tracks a circle counter clockwise** in the d-q plane.

Sensorless operation

The **currents** in the actual reference frame i_d and i_q are related to their **references** i_d^* and i_q^* through a **rotation** of $\Delta\vartheta$ represented by the rotation matrix $R(\Delta\vartheta)$.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = R(\Delta\vartheta) \begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} = \begin{bmatrix} \cos(\Delta\vartheta) & -\sin(\Delta\vartheta) \\ \sin(\Delta\vartheta) & \cos(\Delta\vartheta) \end{bmatrix} \begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix}$$

The reference current vector can be written in **polar coordinates**

$$i_d^* = |i^*| \cos(\vartheta^*)$$
$$i_q^* = |i^*| \sin(\vartheta^*)$$

So the **actual working point** of the machine can be written as a **function** of the **reference current** vector $\bar{i^*} = (|i^*|, \vartheta_i^*)$ and of the position **estimation error** $\Delta\vartheta$.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} f(|i^*|, \vartheta_i^*, \Delta\vartheta) \\ g(|i^*|, \vartheta_i^*, \Delta\vartheta) \end{bmatrix}$$

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Sensorless operation

Consequences of position estimation error:

- **Reduced Efficiency**: even if the control algorithm commands a working point on the MTPA, in presence of an estimation error the machine works on another, less efficient, point.

- **Poor Speed/Torque control**: torque is different in different points of the *dq* plain. With significant position estimation error the torque can change its sign leading to the loss of control of the drive.

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High Frequency Voltage Injection Position Estimation

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Notation

The **currents** of a sensorless drive with high frequency injection are made of **two terms**

$$i_d = I_d + i_{hd}$$
$$i_q = I_q + i_{hq}$$

- **low frequency** term (I_d, I_q) –> working point defined by the speed and current control
- **high frequency** term (i_{hd}, i_{hq}) –> due to the injection for the position estimation

The reference current vector refers to the low frequency currents

$$\bar{I}^* = (I_d^*, I_q^*) = (|I^*|, \vartheta_I^*)$$

Two reference frames are used

- **actual frame** with angle ϑ_{me} –> $\bar{i}_h = (i_{hd}, i_{hq}) = (|i_h|, \vartheta_{hi})$ and $\bar{I} = (I_d, I_q) = (|I|, \vartheta_I)$
- **estimated frame** with angle $\tilde{\vartheta}_{me}$ –> $\bar{i}_h^x = (i_{hd}^x, i_{hq}^x) = (|i_h^x|, \vartheta_{hi}^x)$ and $\bar{I}^x = (I_d^x, I_q^x) = (|I^x|, \vartheta_I^x)$

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HF Voltage Injection: pulsating flux vector

High frequency sinusoidal voltages are injected into the stator windings

$$u_{hd}^{x} = U_{hd}\cos(\omega_h t)$$
$$u_{hq}^{x} = U_{hq}\sin(\omega_h t)$$

and, if the relationship $U_{hq} = U_{hd}\frac{\omega_{me}}{\omega_h}$ is observed, result in the following **high frequency pulsating flux vector**

$$\lambda_{hd}^{x} = \Lambda_{hd}\sin(\omega_h t) = \frac{U_{hd}}{\omega_h}\sin(\omega_h t)$$
$$\lambda_{hq}^{x} = \Lambda_{hq}\cos(\omega_h t) = 0$$

The injection induces **high frequency currents** in the stator windings.

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Ideal case: current response

Assumptions:

- NO iron saturation –> L_d and L_q are constant
- NO cross-coupling –> $L_{dq} = 0$

The **flux/current relationship** is used to calculate the resulting high frequency current.

$$\begin{bmatrix} \lambda_{hd} \\ \lambda_{hq} \end{bmatrix} = \underbrace{\begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix}}_{L} \begin{bmatrix} i_{hd} \\ i_{hq} \end{bmatrix}$$

Vectors in the actual frame are obtained from the ones **in the estimated frame through a rotation of** $\Delta\vartheta$ so the flux/current relationship becomes

$$\begin{bmatrix} \lambda^x_{hd} \\ \lambda^x_{hq} \end{bmatrix} = \underbrace{R(-\Delta\vartheta) \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} R(\Delta\vartheta)}_{L^x} \begin{bmatrix} i^x_{hd} \\ i^x_{hq} \end{bmatrix}$$

where $R(\Delta\vartheta)$ is a rotation matrix.

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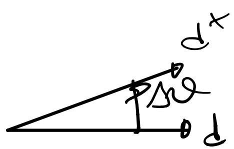
$$L^x = \begin{bmatrix} L_\Sigma - L_\Delta \cos(2\Delta\vartheta) & L_\Delta \sin(2\Delta\vartheta) \\ L_\Delta \sin(2\Delta\vartheta) & L_\Sigma + L_\Delta \cos(2\Delta\vartheta) \end{bmatrix}$$

with $\quad L_\Sigma = \dfrac{(L_q + L_d)}{2} \quad$ and $\quad L_\Delta = \dfrac{(L_q - L_d)}{2}$

The **flux/current relationship** can be **inverted** and the **high frequency flux vector** substituted into the equation

$$\begin{bmatrix} i^x_{hd} \\ i^x_{hq} \end{bmatrix} = (L^x)^{-1} \begin{bmatrix} \lambda^x_{hd} \\ \lambda^x_{hq} \end{bmatrix} = (L^x)^{-1} \begin{bmatrix} \frac{U_{hd}}{\omega_h} \sin(\omega_h t) \\ 0 \end{bmatrix}$$

leading to the following expression for the **high frequency currents**



$$i^x_{hd} = \frac{U_{hd}}{\omega_h L_d L_q}[L_\Sigma - L_\Delta \cos(2\Delta\vartheta)] \sin(\omega_h t)$$

$$i^x_{hq} = \underbrace{-\frac{U_{hd}}{\omega_h L_d L_q}[L_\Delta \sin(2\Delta\vartheta)]}_{I_{hq}} \sin(\omega_h t)$$

The q **current amplitude** I_{hq} **contains position information.**

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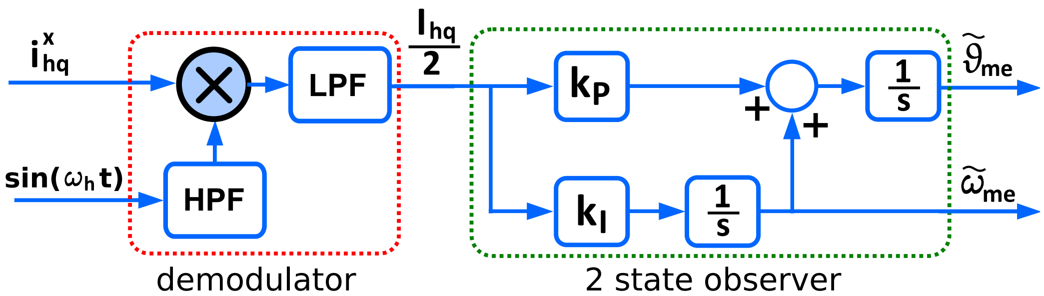
In order to get the position estimation

- a **demodulator** extracts I_{hq}
- that is **nullified** by a **2 state observer**.

$$I_{hq} = -\frac{U_{hd}}{\omega_h L_d L_q}[L_\Delta \sin(2\Delta\vartheta)] = 0$$



- with $I_{hq} > 0$ –> $\tilde{\vartheta}_{me}$ increases –> $\Delta\vartheta = \tilde{\vartheta}_{me} - \vartheta_{me}$ increases
- with $I_{hq} < 0$ –> $\tilde{\vartheta}_{me}$ decreases –> $\Delta\vartheta = \tilde{\vartheta}_{me} - \vartheta_{me}$ decreases

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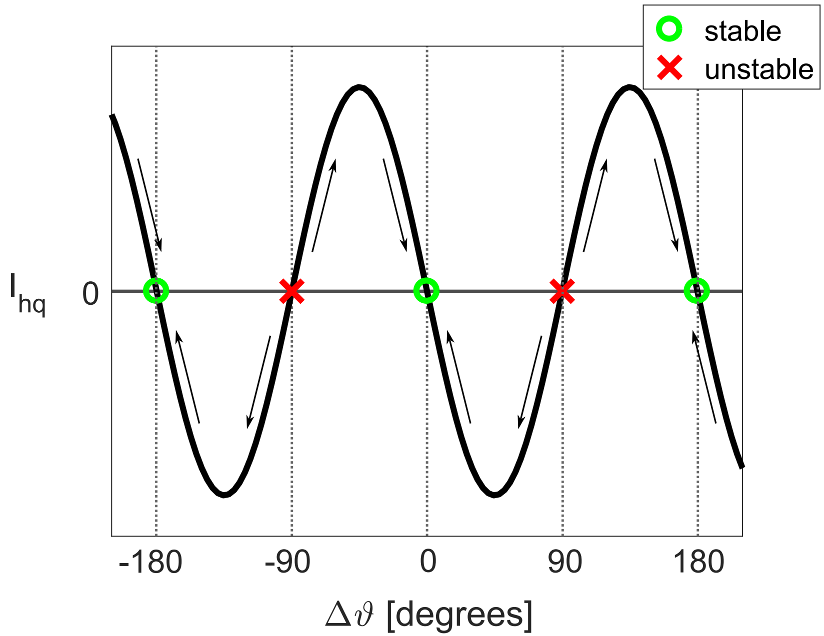
$$I_{hq} = -\frac{U_{hd}}{\omega_h L_d L_q}[L_\Delta \sin(2\Delta\vartheta)] = 0$$



By nullifying I_{hq} **4 convergence points** can be found:

- **2 stable points**
  $\Delta\vartheta = 0$ and $\Delta\vartheta = \pi$
- **2 unstable points**
  $\Delta\vartheta = \frac{\pi}{2}$ and $\Delta\vartheta = \frac{3\pi}{2}$

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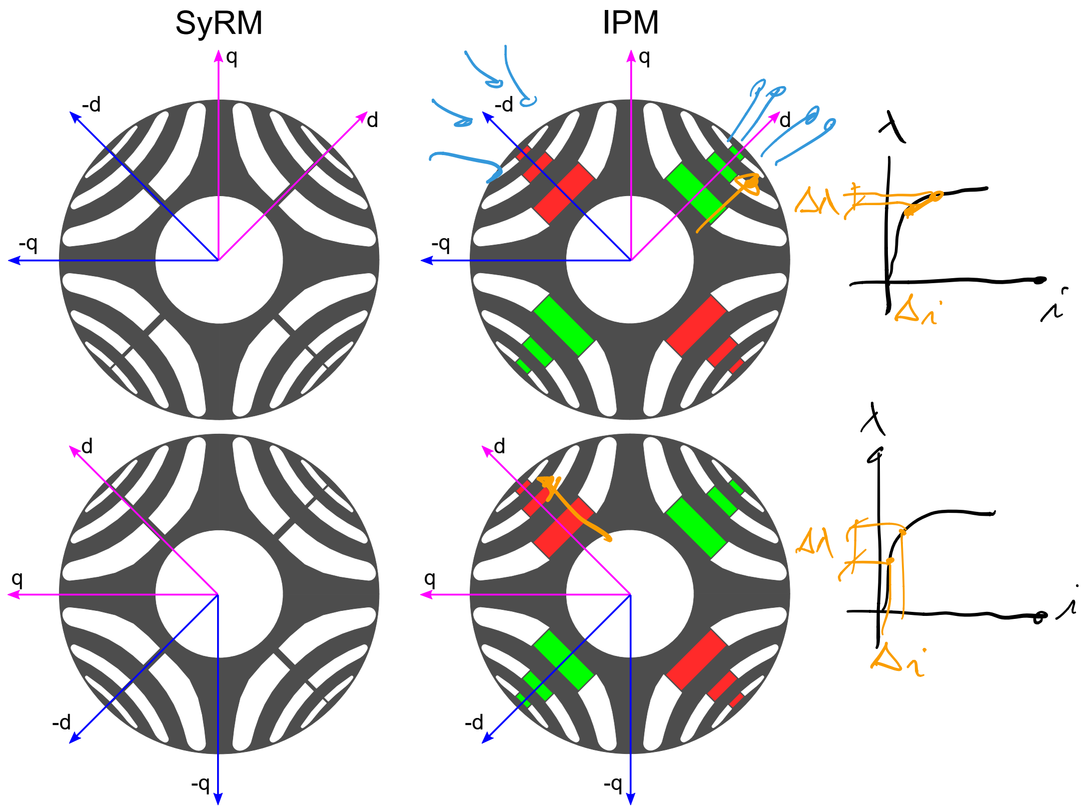

- In **IPM machine specific techniques** are necessary to **distinguish between** the **stable points**.
- In **SyR** it is **not necessary** since the rotor is symmetrical.

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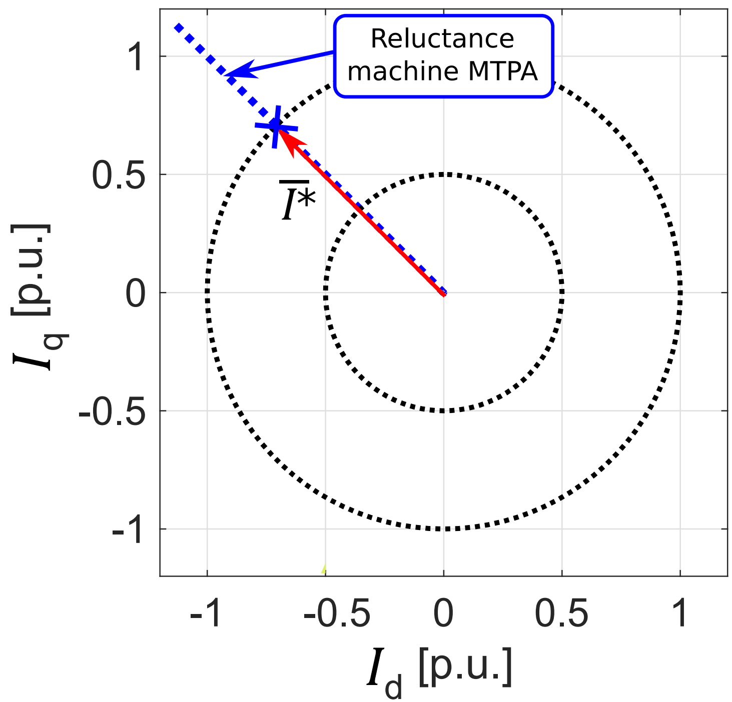
Convergence map in the I_d-I_q plane



The **reference current vector** is assumed to be taken **on the MTPA**

$$\vartheta_I^* = \vartheta_{MTPA}$$

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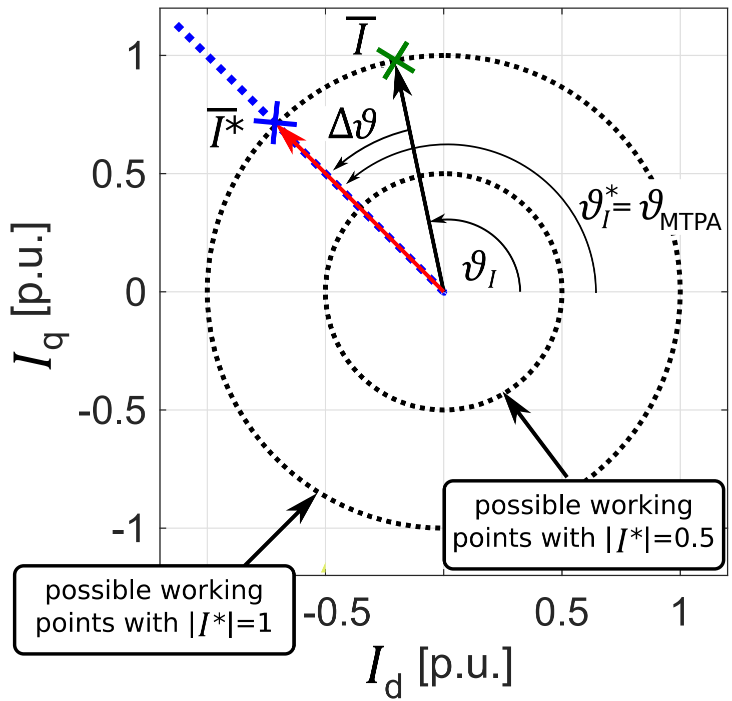
Convergence map in the I_d-I_q plane



Every point of the plane $(I_d, I_q) = (|I|, \vartheta_I)$ **is the working point of the sensorless drive** obtained when

- the amplitude of the reference current is $|I^*| = |I|$
- the estimation error is $\Delta\vartheta = \vartheta_I^* - \vartheta_I = \vartheta_{MTPA} - \vartheta_I$

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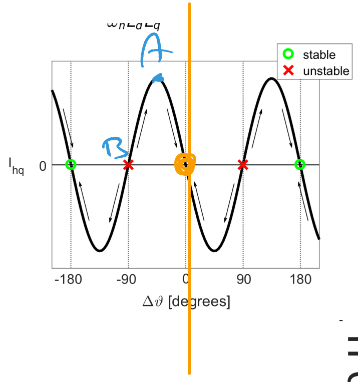
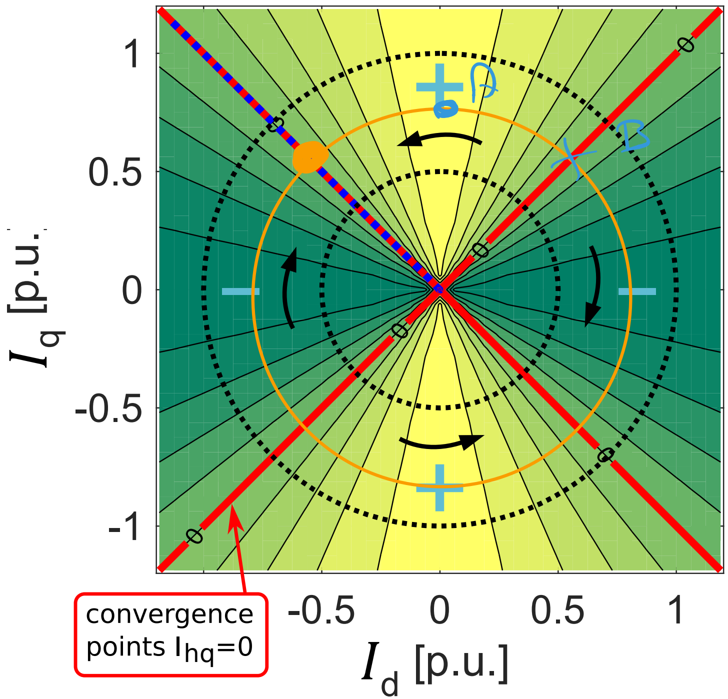


Convergence map in the I_d-I_q plane



Given $\Delta\vartheta$ it is possible to calculate the I_{hq} for every point of the plane.

No estimation error is present and the control is able to **drive** the **machine** in the **desired working points**

With cross-coupling: current response

Assumptions:

- NO iron saturation –> L_d and L_q are constant
- With cross-coupling –> $L_{dq} \neq 0$ constant

The **flux/current relationship** is used to calculate the resulting high frequency current.

$$\begin{bmatrix} \lambda_{hd} \\ \lambda_{hq} \end{bmatrix} = \underbrace{\begin{bmatrix} L_d & L_{dq} \\ L_{dq} & L_q \end{bmatrix}}_{L} \begin{bmatrix} i_{hd} \\ i_{hq} \end{bmatrix}$$

Vectors in the actual frame are obtained from the vector **in the estimated frame through a rotation of** $\Delta\vartheta$ so the flux/current relationship becomes

$$\begin{bmatrix} \lambda^x_{hd} \\ \lambda^x_{hq} \end{bmatrix} = \underbrace{R(-\Delta\vartheta) \begin{bmatrix} L_d & L_{dq} \\ L_{dq} & L_q \end{bmatrix} R(\Delta\vartheta)}_{L^x} \begin{bmatrix} i^x_{hd} \\ i^x_{hq} \end{bmatrix}$$

where $R(\Delta\vartheta)$ is a rotation matrix.

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$$L^x = \begin{bmatrix} L_\Sigma - L_\Delta \cos(2\Delta\vartheta) + L_{dq}\sin(2\Delta\vartheta) & L_\Delta \sin(2\Delta\vartheta) + L_{dq}\cos(2\Delta\vartheta) \\ L_\Delta \sin(2\Delta\vartheta) + L_{dq}\cos(2\Delta\vartheta) & L_\Sigma + L_\Delta \cos(2\Delta\vartheta) - L_{dq}\sin(2\Delta\vartheta) \end{bmatrix}$$

$$\text{with} \quad L_\Sigma = \frac{(L_d + L_q)}{2} \quad \text{and} \quad L_\Delta = \frac{(L_q - L_d)}{2}$$

The **flux/current relationship** can be **inverted** and the **pulsating flux vector** substituted into the equation

$$\begin{bmatrix} i^x_{hd} \\ i^x_{hq} \end{bmatrix} = (L^x)^{-1} \begin{bmatrix} \lambda^x_{hd} \\ \lambda^x_{hq} \end{bmatrix} = (L^x)^{-1} \begin{bmatrix} \frac{U_{hd}}{\omega_h} \sin(\omega_h t) \\ 0 \end{bmatrix}$$

leading to the following expression for the **high frequency currents**

$$i^x_{hd} = \frac{U_{hd}}{\omega_h (L_d L_q - L^2_{dq})} [L_\Sigma - L_\Delta \cos(2\Delta\vartheta) - L_{dq}\sin(2\Delta\vartheta)] \sin(\omega_h t)$$

$$i^x_{hq} = \underbrace{-\frac{U_{hd}}{\omega_h (L_d L_q - L^2_{dq})} [L_\Delta \sin(2\Delta\vartheta) + L_{dq}\cos(2\Delta\vartheta)]}_{I_{hq}} \sin(\omega_h t)$$

The q **current amplitude** I_{hq} **contains different position information.**

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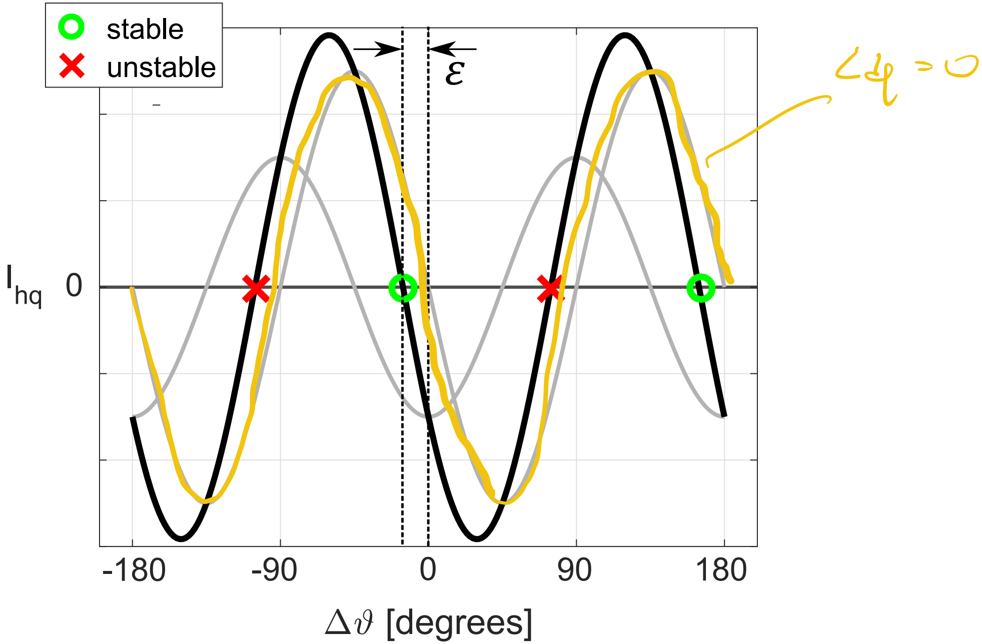
The convergence points are the solutions of $I_{hq} = 0$:

$$-\frac{U_{hd}}{\omega_h(L_d L_q - L_{dq}^2)}[L_\Delta \sin(2\Delta\vartheta) + L_{dq}\cos(2\Delta\vartheta)] = 0$$



The **estimated position** is **affected by** an **error**.

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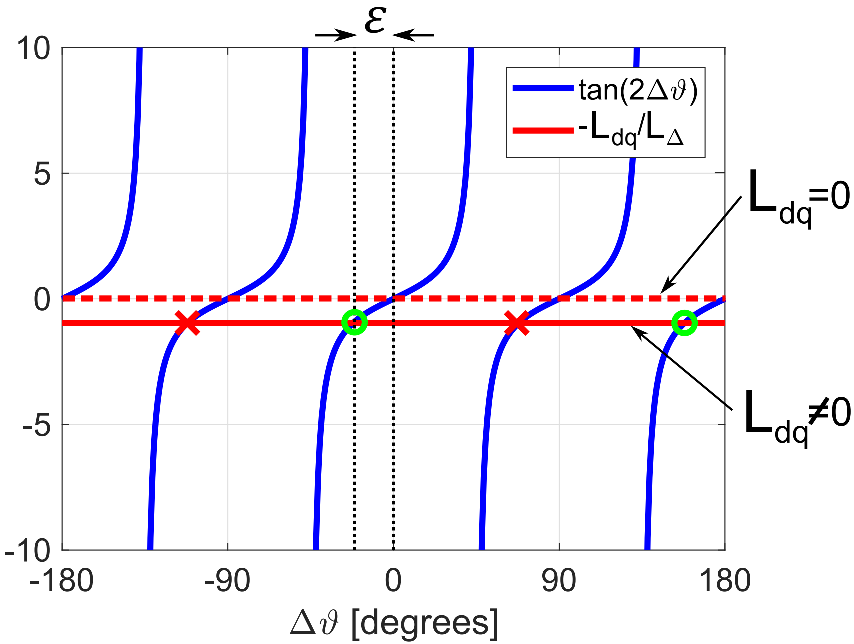
$$[L_\Delta \sin(2\Delta\vartheta) + L_{dq}\cos(2\Delta\vartheta)] = 0 \;\rightarrow\; tan(2\Delta\vartheta) = -\frac{L_{dq}}{L_\Delta}$$



The **estimation error** is

$$\varepsilon = \frac{1}{2} tan^{-1}(-\frac{L_{dq}}{L_\Delta})$$

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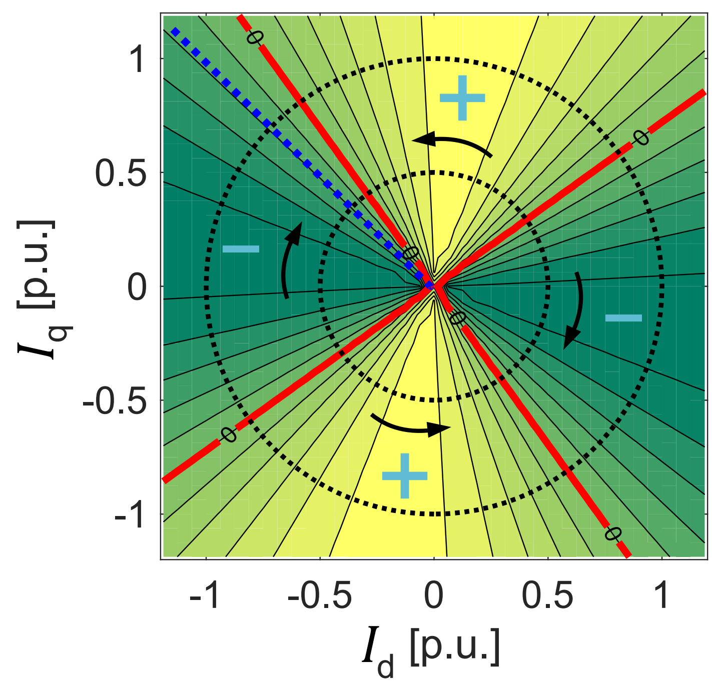
Convergence map in the I_d-I_q plane



The estimation converges with an **error** so the **actual** machine **working point** is **different from the reference**, i.e. the machine does not work in MTPA.

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Real machine: high frequency model

No simplifying assumptions:

- With iron saturation
- With cross-coupling

The **flux/current relationship** is

$$\begin{bmatrix} \lambda_d \\ \lambda_q \end{bmatrix} = \begin{bmatrix} \lambda_d(i_d, i_q) \\ \lambda_q(i_d, i_q) \end{bmatrix}$$

The **currents** of a **sensorless drive** with high frequency injection are made of **two terms**

$$i_d = I_d + i_{hd}$$
$$i_q = I_q + i_{hq}$$

- (I_d, I_q) –> working point given by the speed and current control
- (i_{hd}, i_{hq}) –> due to the injection, for the position estimation

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The **flux/current relationship** is **linearised around the working point** (I_d, I_q)

$$\lambda_d = \lambda_d(I_d, I_q) + \underbrace{\left.\frac{\partial \lambda_d(i_d, i_q)}{\partial i_d}\right|_{I_d, I_q}}_{\ell_d} i_{hd} + \underbrace{\left.\frac{\partial \lambda_d(i_d, i_q)}{\partial i_q}\right|_{I_d, I_q}}_{\ell_{dq}} i_{hq}$$

$$\lambda_q = \lambda_q(I_d, I_q) + \underbrace{\left.\frac{\partial \lambda_q(i_d, i_q)}{\partial i_d}\right|_{I_d, I_q}}_{\ell_{dq}} i_{hd} + \underbrace{\left.\frac{\partial \lambda_q(i_d, i_q)}{\partial i_q}\right|_{I_d, I_q}}_{\ell_q} i_{hq}$$

If only the **high frequency flux** is considered and the **differential inductances** ℓ_d, ℓ_q, ℓ_{dq} are defined, the following **high frequency flux/current model** can be written as

$$\begin{bmatrix} \lambda_{hd} \\ \lambda_{hq} \end{bmatrix} = \underbrace{\begin{bmatrix} \ell_d(I_d, I_q) & \ell_{dq}(I_d, I_q) \\ \ell_{dq}(I_d, I_q) & \ell_q(I_d, I_q) \end{bmatrix}}_{\ell} \begin{bmatrix} i_{hd} \\ i_{hq} \end{bmatrix}$$

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Real case: current response

Similarly to the previous cases the **high frequency currents** due to the **pulsating flux vector** can be calculated

$$i_{hd}^{x} = \frac{U_{hd}[\ell_\Sigma(I_d, I_q) - \ell_\Delta(I_d, I_q)\cos(2\Delta\vartheta) - \ell_{dq}(I_d, I_q)\sin(2\Delta\vartheta)]}{\omega_h[\ell_d(I_d, I_q)\ell_q(I_d, I_q) - \ell_{dq}^2(I_d, I_q)]}\sin(\omega_h t)$$

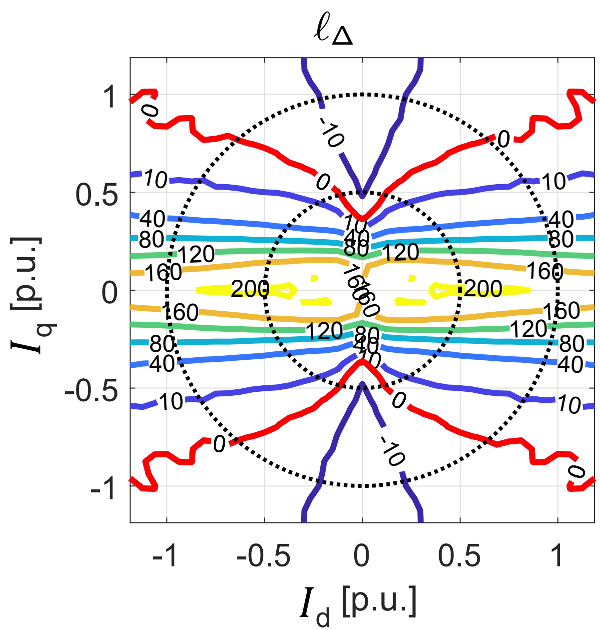
$$i_{hq}^{x} = \underbrace{-\frac{U_{hd}[\ell_\Delta(I_d, I_q)\sin(2\Delta\vartheta) + \ell_{dq}(I_d, I_q)\cos(2\Delta\vartheta)]}{\omega_h[\ell_d(I_d, I_q)\ell_q(I_d, I_q) - \ell_{dq}^2(I_d, I_q)]}}_{I_{hq}}\sin(\omega_h t)$$

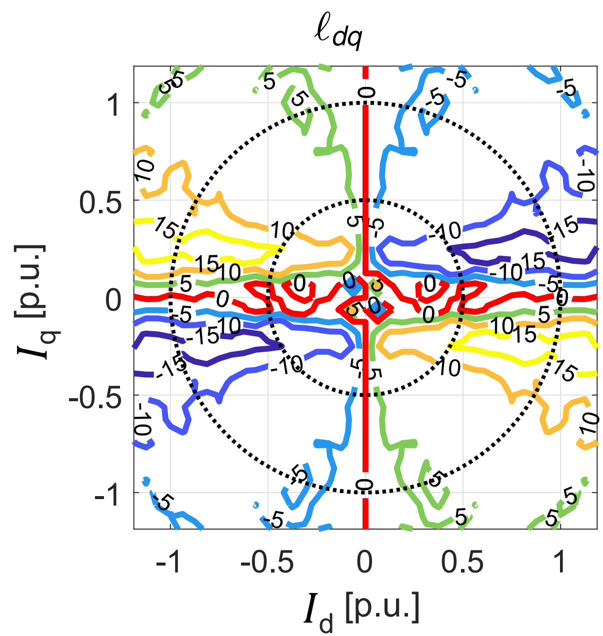
with $\ell_\Sigma(I_d, I_q) = \frac{(\ell_d(I_d,I_q)+\ell_q(I_d,I_q))}{2}$ and $\ell_\Delta(I_d, I_q) = \frac{(\ell_q(I_d,I_q)-\ell_d(I_d,I_q))}{2}$

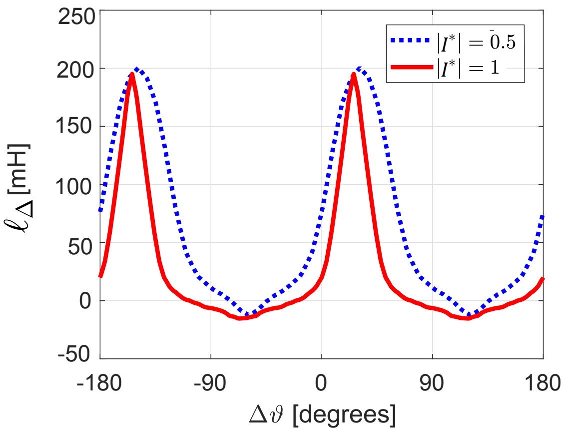
The **dependence on** the reference **current angle** can be **neglected** since it is assumed equal to the MTPA angle ϑ_{MTPA}.

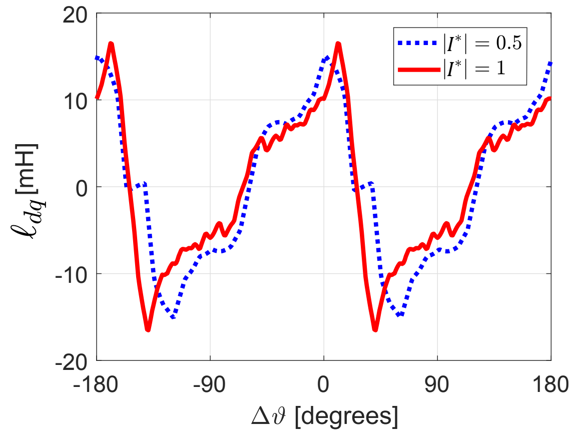
$$\begin{aligned} I_d &= f(|I^*|, \Delta\vartheta) \\ I_q &= g(|I^*|, \Delta\vartheta) \end{aligned} \quad \Rightarrow \quad \begin{aligned} \ell_d &= \ell_d(|I^*|, \Delta\vartheta) & \ell_q &= \ell_q(|I^*|, \Delta\vartheta) \\ \ell_{dq} &= \ell_{dq}(|I^*|, \Delta\vartheta) & \ell_\Delta &= \ell_\Delta(|I^*|, \Delta\vartheta) \end{aligned}$$

Like the working point, also the **inductances vary according to** the **estimation error** $\Delta\vartheta$ and the **required current** vector $\bar{I}^*$.









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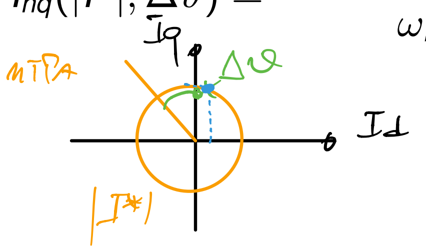
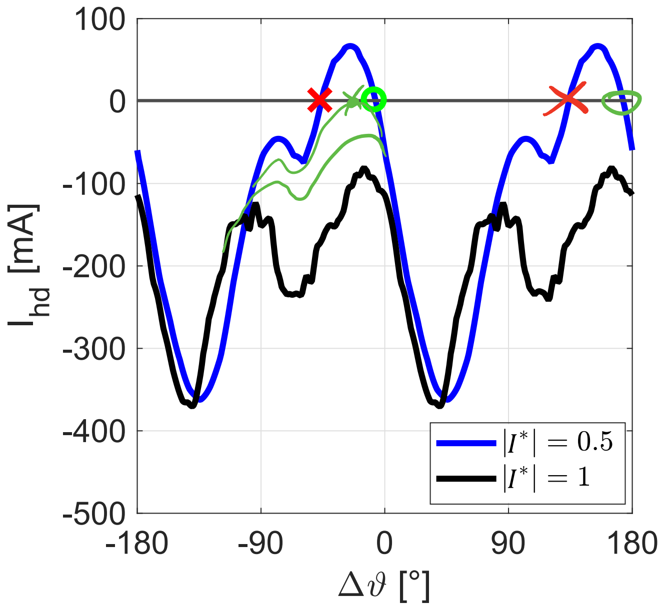
The *q* **current amplitude** I_{hq} can be written as a **function of** $\Delta\vartheta$ and $|I^*|$

$$I_{hq}(|I^*|, \Delta\vartheta) = -\frac{U_{hd}[\ell_\Delta(|I^*|, \Delta\vartheta)\sin(2\Delta\vartheta) + \ell_{dq}(|I^*|, \Delta\vartheta)\cos(2\Delta\vartheta)]}{\omega_h[\ell_d(|I^*|, \Delta\vartheta)\ell_q(|I^*|, \Delta\vartheta) - \ell_{dq}^2(|I^*|, \Delta\vartheta)]}$$



The convergence points are the solutions of $I_{hq} = 0$:

$$-\frac{U_{hd}[\ell_\Delta(|I^*|,\Delta\vartheta)\sin(2\Delta\vartheta)+\ell_{dq}(|I^*|,\Delta\vartheta)\cos(2\Delta\vartheta)]}{\omega_h[\ell_d(|I^*|,\Delta\vartheta)\ell_q(|I^*|,\Delta\vartheta)-\ell_{dq}^2(|I^*|,\Delta\vartheta)]}=0$$



At the **nominal current I_{hq} does not cross zero**.

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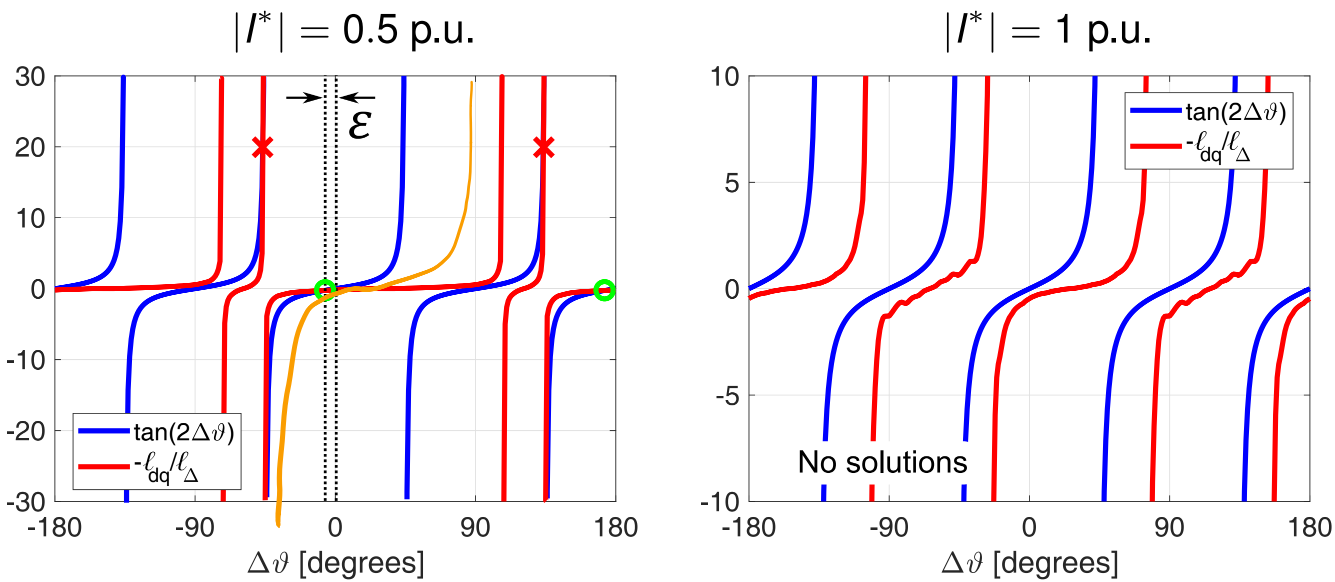
The observer nullifies I_{hq} so the algorithm converges to the solution of

$$[\ell_\Delta(|I^*|, \Delta\vartheta)\sin(2\Delta\vartheta) + \ell_{dq}(|I^*|, \Delta\vartheta)\cos(2\Delta\vartheta)] = 0$$

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



At the **nominal current no solutions** can be found.

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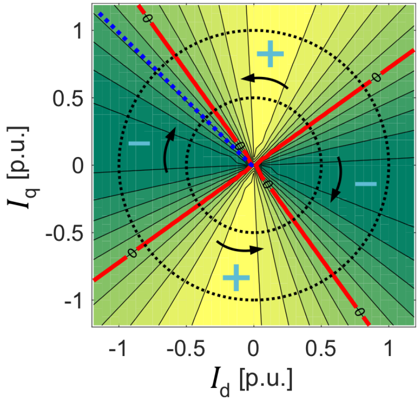
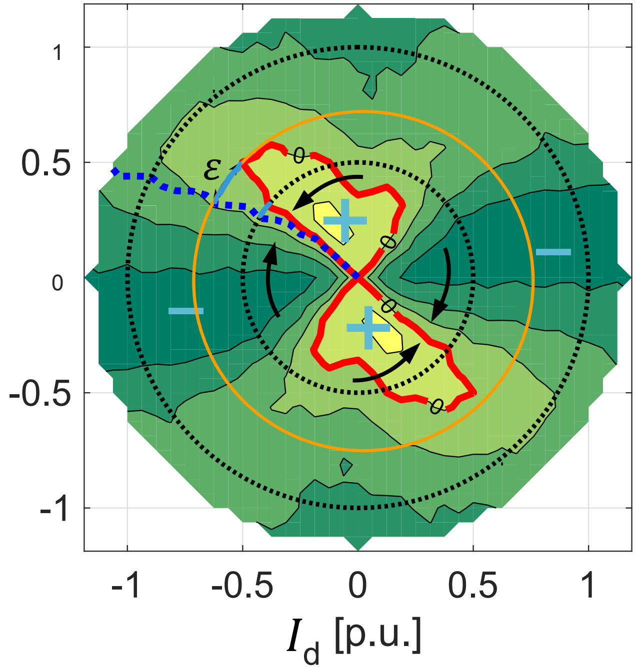
Convergence map in the I_d-I_q plane





At the **nominal current** the **estimation** does **not converge**.

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Convergence range extension

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Compensations

Two types of **compensation** can be incorporated for

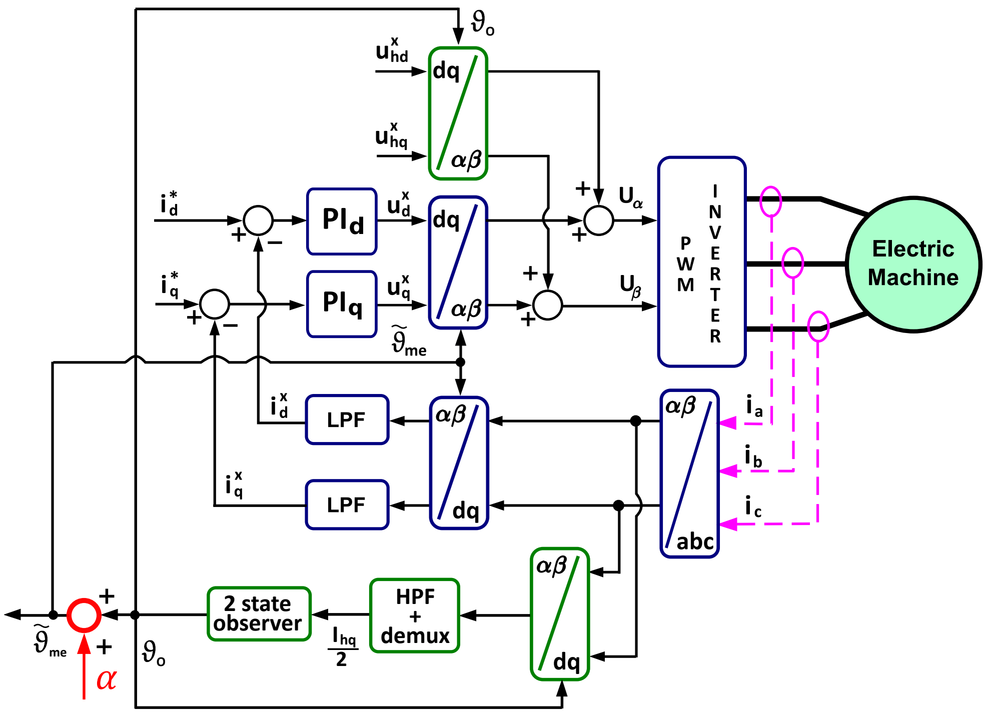
- achieving **convergence** at any current
- increasing **robustness**
- increasing **accuracy**

The possible compensations are:

- **angle compensation**
- **current compensation**

Angle compensation

The angle compensation consists in **adding an angle** $\alpha = -\varepsilon(\bar{I}^*)$ to **compensate the estimation error**.



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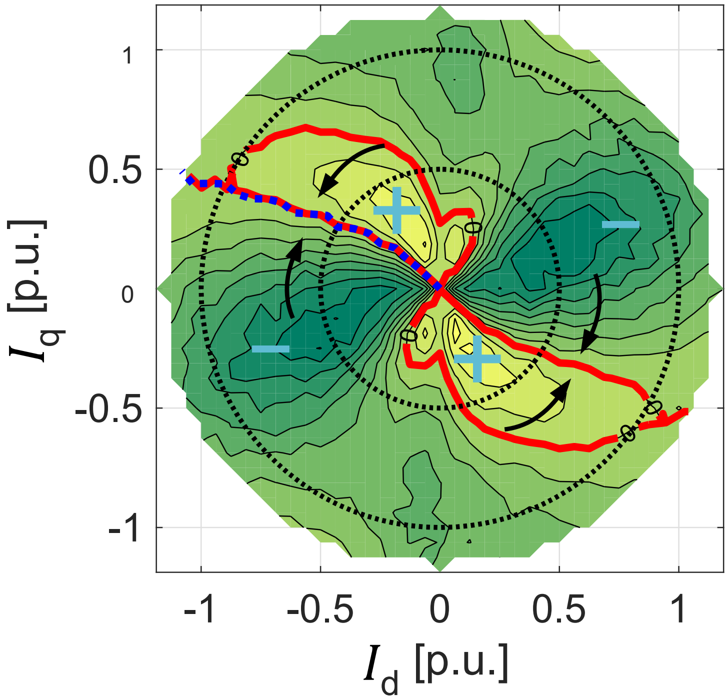
Convergence map in the I_d-I_q plane



The stable **convergence points coincide with** the desired one (i.e. **MTPA** points) so the estimation error has been compensated.

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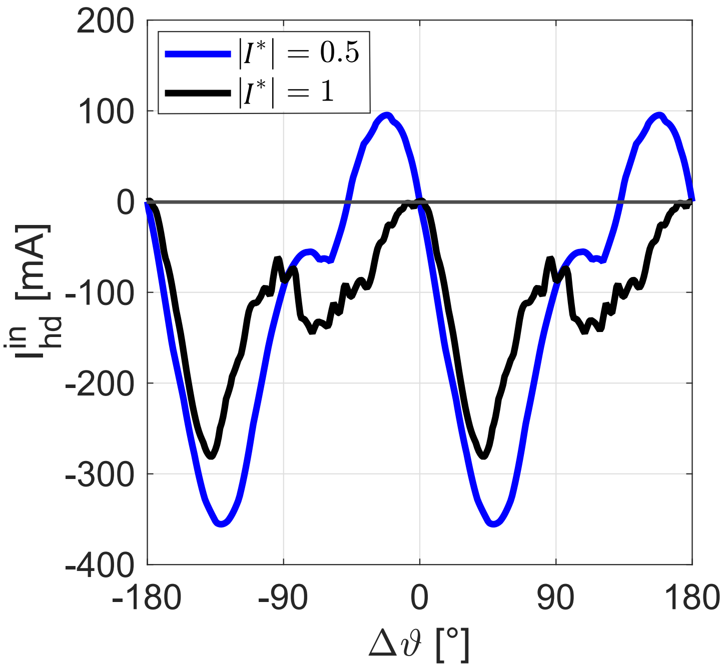

However the convergence **at the nominal current** is only **barely stable** because there is a **low margin between** the **stable** and **unstable** convergence **points**.

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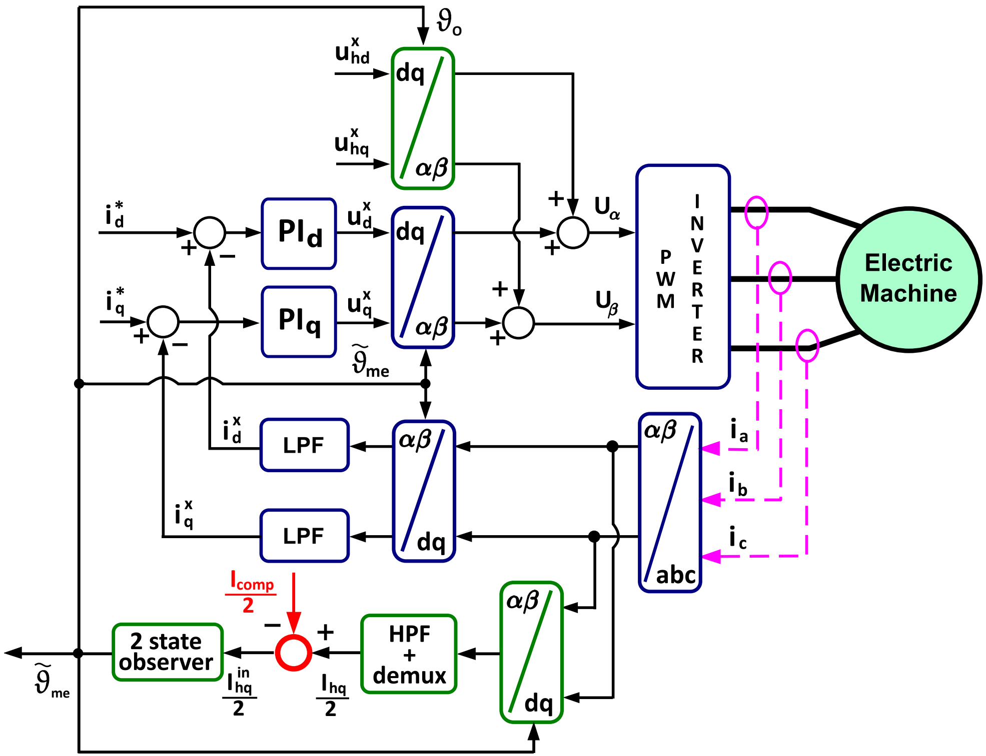
Current compensation

The current compensation consists in **shifting** the I_{hq} **waveform** by adding I_{comp} in order to have $I_{hq}^{in} = 0$ in correspondence of $\Delta\vartheta = 0$.



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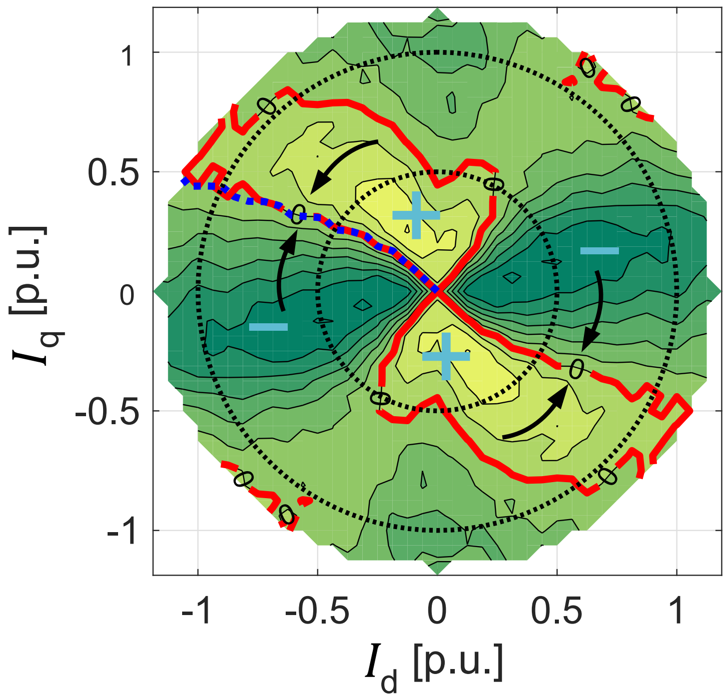
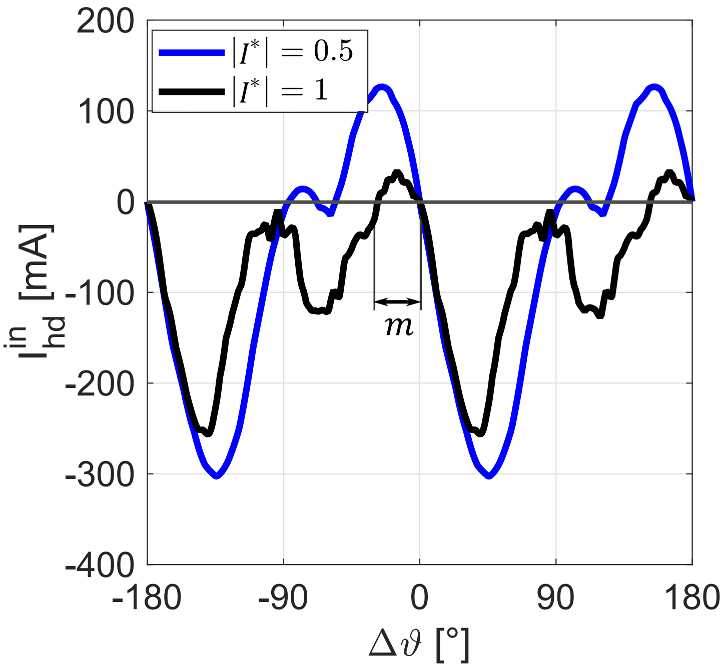
Convergence map in the I_d-I_q plane



The stable **convergence points coincide with** the desired one (i.e. **MTPA** points) so the estimation error has been compensated.



Stable convergence points exist at the **nominal current**.
There is a **higher margin between** the **stable** and **unstable** convergence **points**.

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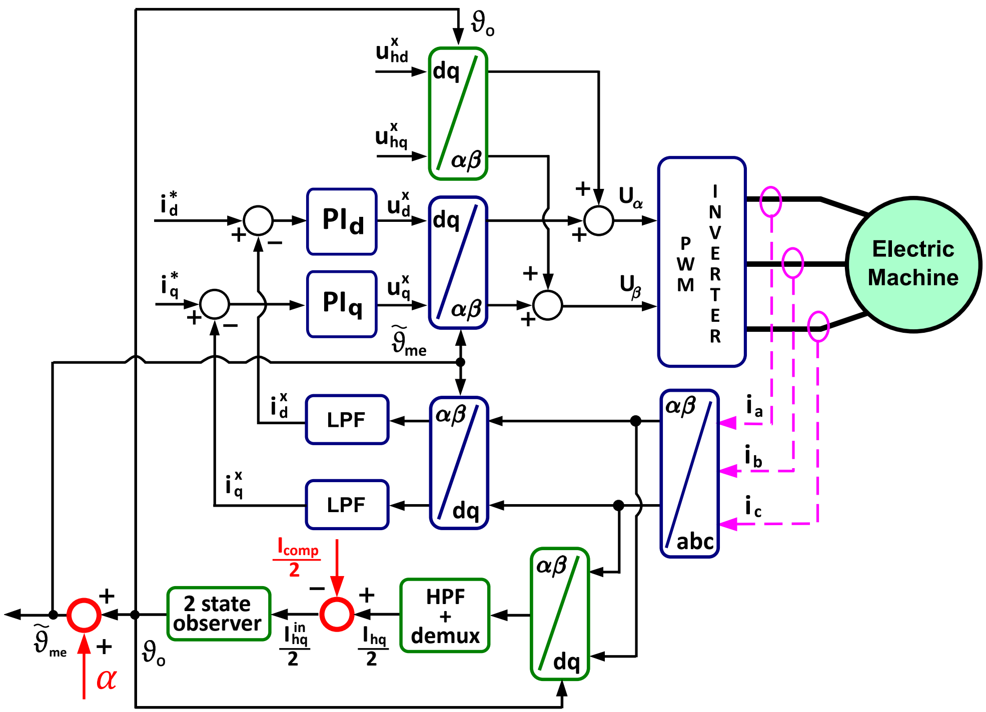
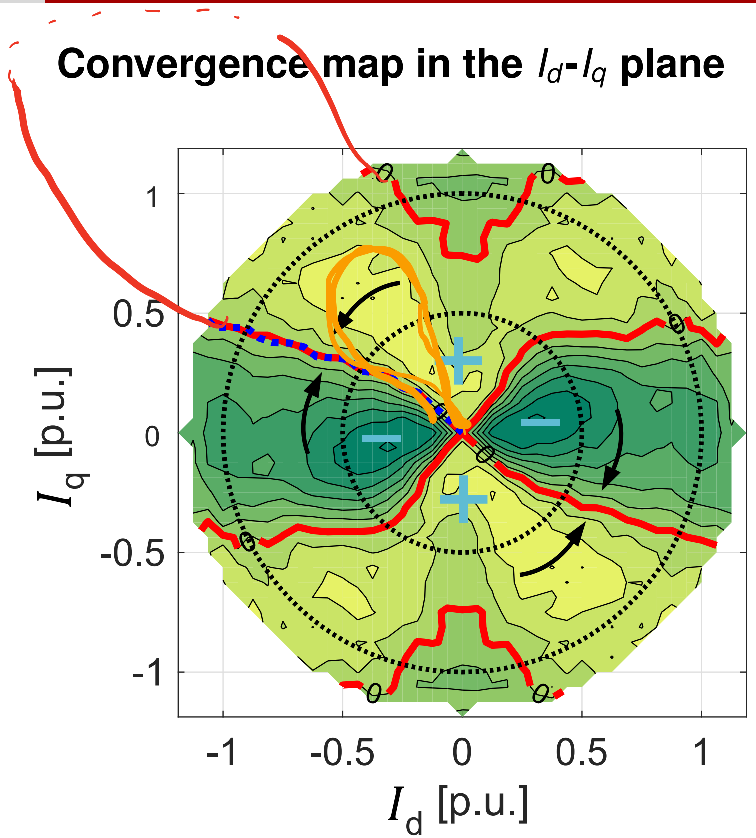
Both compensations

The two **compensations** can be combined and **used together**.



Convergence map in the I_d-I_q plane



The stable **convergence points coincide with** the desired one (i.e. **MTPA** points) so the estimation error has been compensated.

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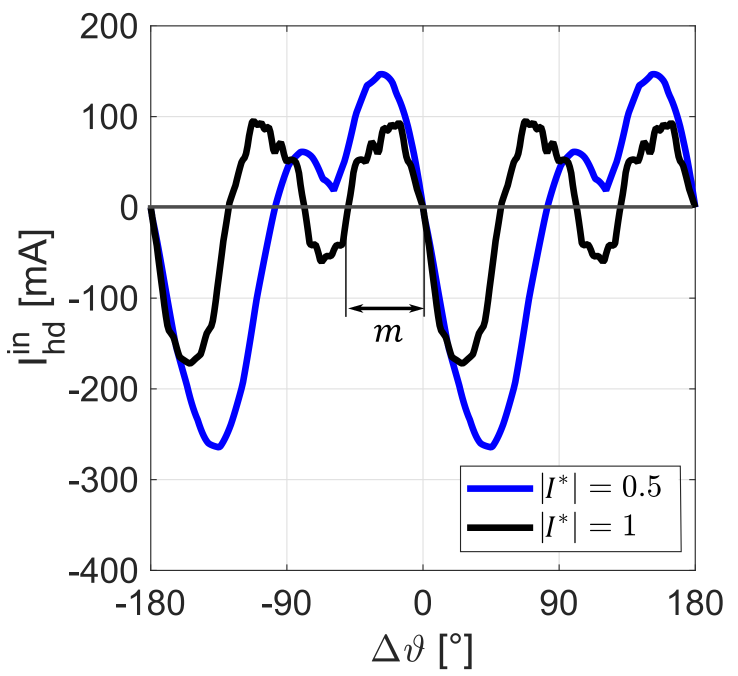
$\lambda_d(i_d, i_q)$
$\lambda_q(i_d, i_q)$
l_d l_q l_{dq}
l_0 l_Σ



With **two** compensation **parameters** the **convergence interval** can be **maximised**.

All the described compensations need the **knowledge of the inductances maps** of the machine.

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Thank you
for your attention