Rotor design arrangement of SPM motors for the sensorless control at low speed and standstill

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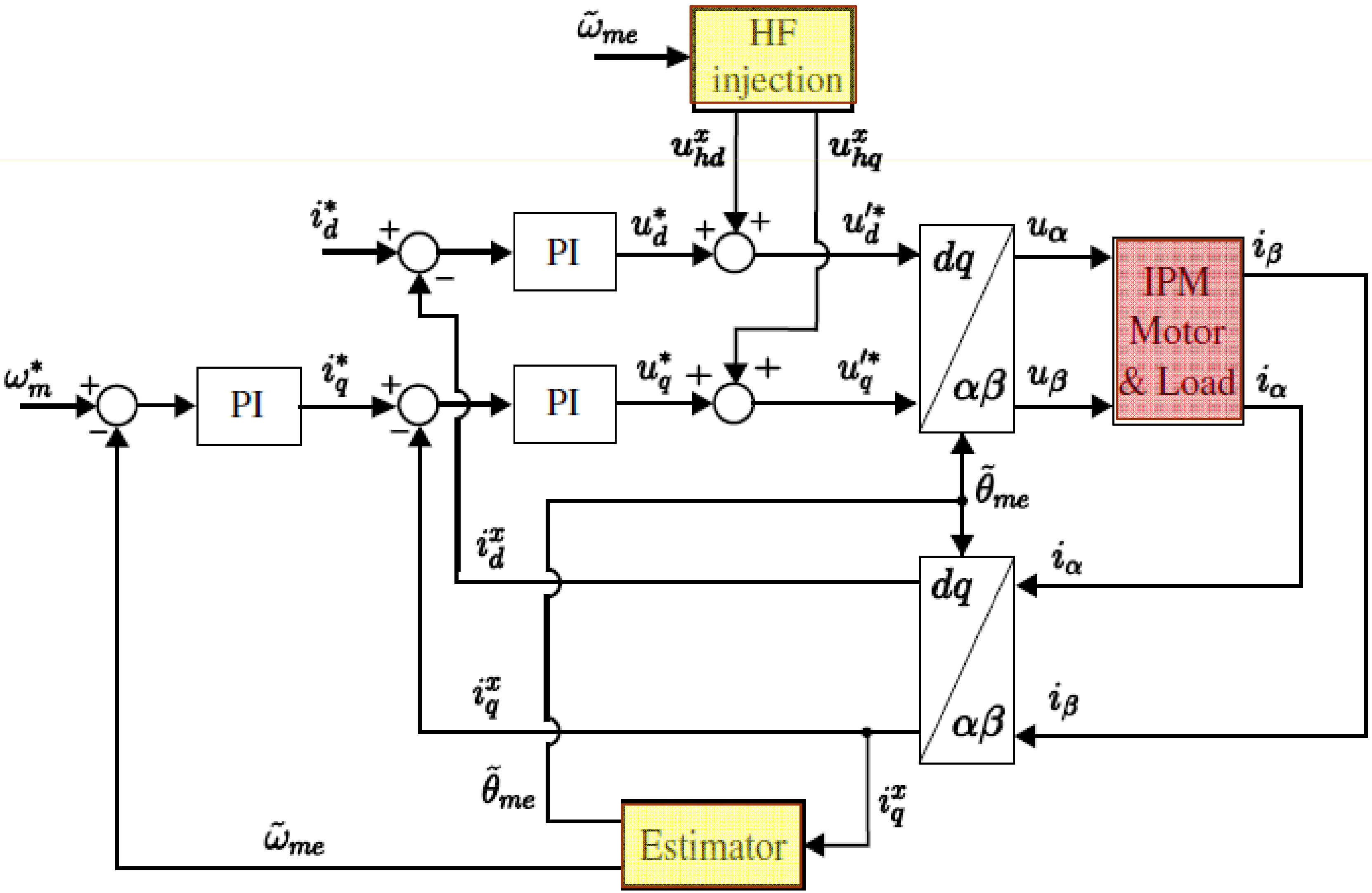
Introduction

- High frequency voltage injection is a well known technique for detecting the position of anisotropic (IPM:Interior PM or Reluctance) rotors at low speed and standstill.
- The paper investigates the possibilities to apply the same method to SPM:Surface-mounted PM rotor (which are, in principle, isotropic).
- The design of small anisotropic figures for the purpose of position detection instead of torque production is illustrated.
- Preliminary test results are also presented and discussed.

HF Voltage Injection technique



HF Voltage Injection technique

Let's solve the motor equations

$$u_d(t) = R_s i_d(t) + L_d \frac{di_d}{dt} - \omega_{me} L_q i_q \quad (1)$$

$$u_q(t) = R_s i_q(t) + L_q \frac{di_q}{dt} + \omega_{me} L_d i_d + \omega_{me} \Lambda_{mg} \quad (2)$$

for

$$u^r_{hd} = U_{hd} \cos \omega_h t \quad (6)$$

$$u^r_{hq} = U_{hq} \sin \omega_h t \quad (7)$$

HF Voltage Injection technique

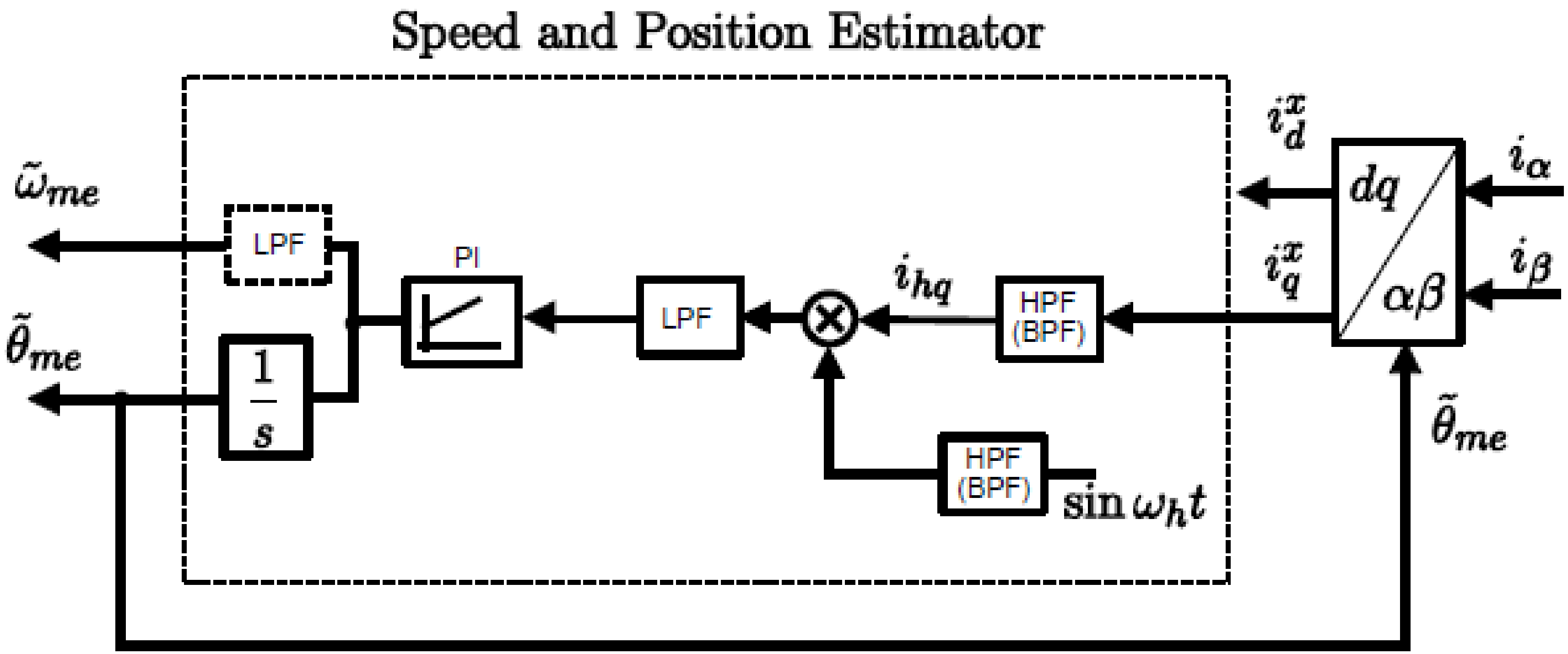
Neglecting Rs effects and assuming $U_{hq} = U_{hd}\omega_{me}/\omega_h$ it results

$$i^r_{hd} = \frac{U_{hd}}{\omega_h}\left(\frac{L_\Sigma \cos 2\Delta\theta}{L_d L_q}\right)\sin\omega_h t$$
$$i^r_{hq} = -\frac{U_{hd}}{\omega_h}\left(\frac{L_\Delta \sin 2\Delta\theta}{L_d L_q}\right)\sin\omega_h t \qquad (10)$$

- $i_{hq}=0 \Rightarrow \Delta\theta=0$
- Anisotropy ($L_\Delta \neq 0$) is needed

with $L_\Sigma = (L_q + L_d)/2$, $L_\Delta = (L_q - L_d)/2$ and $\Delta\theta = \hat{\theta}_{me} - \theta_{me}$, that is the error between the estimated position $\hat{\theta}_{me}$ and the actual one θ_{me}.

HF Voltage Injection technique



HF Voltage Injection technique

- In principle HF Voltage Injection technique cannot be applied to SPM motors because $L_\Delta=0$

- In practice SPM motors may exhibits a small saliency: $L_\Delta=10\%\ L_\Sigma$ because of the iron saturation due to PM
  - Thus HF Voltage Injection technique might work

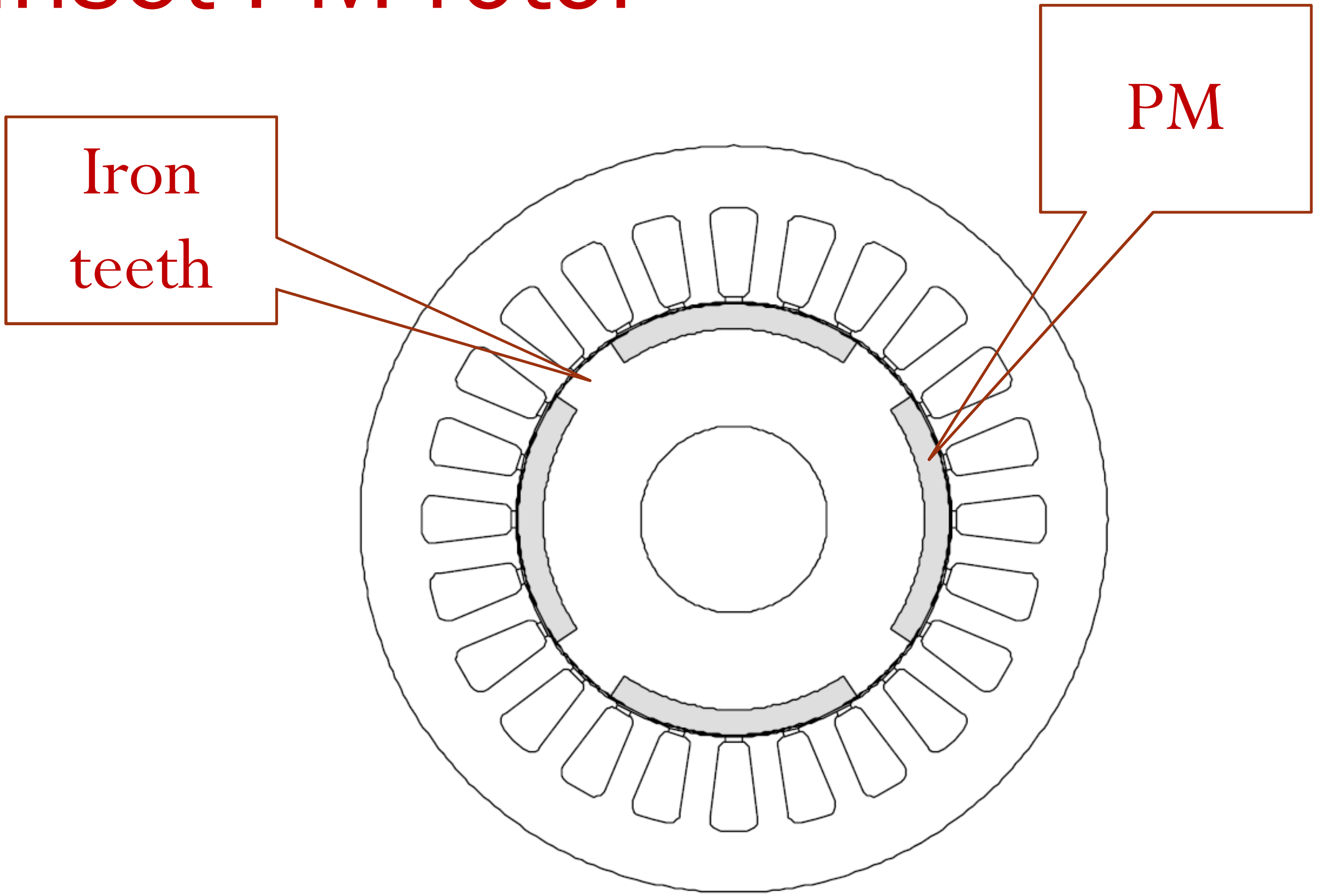
however

- It is not guaranteed
- Saturation map depends on load conditions

HF Voltage Injection technique

- Two modified SPM rotor configurations are proposed here to allows sensorless rotor position detection at low speed and at standstill:
  - **Inset PM rotor**
  - **Ringed-pole SPM rotor**

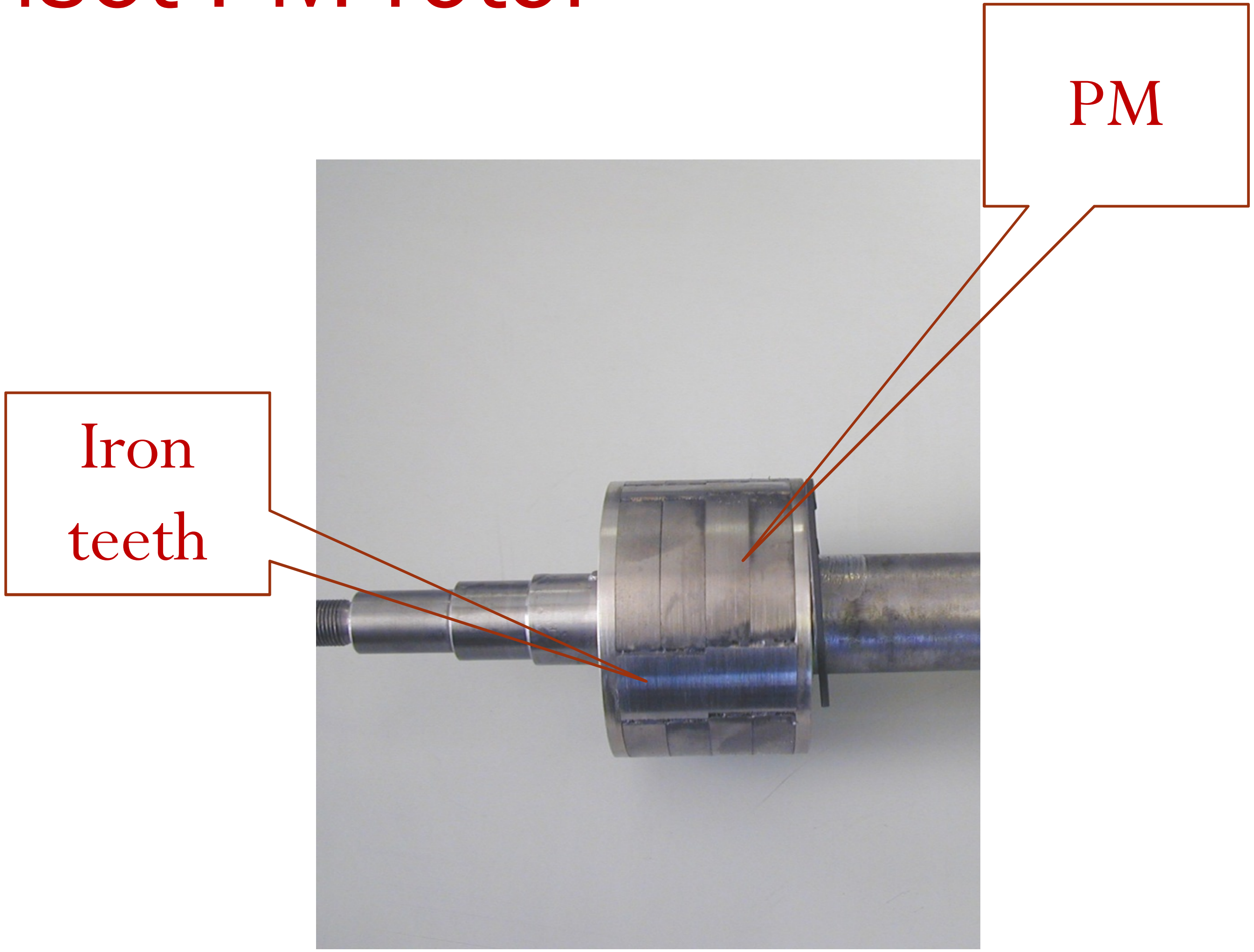
Inset PM rotor



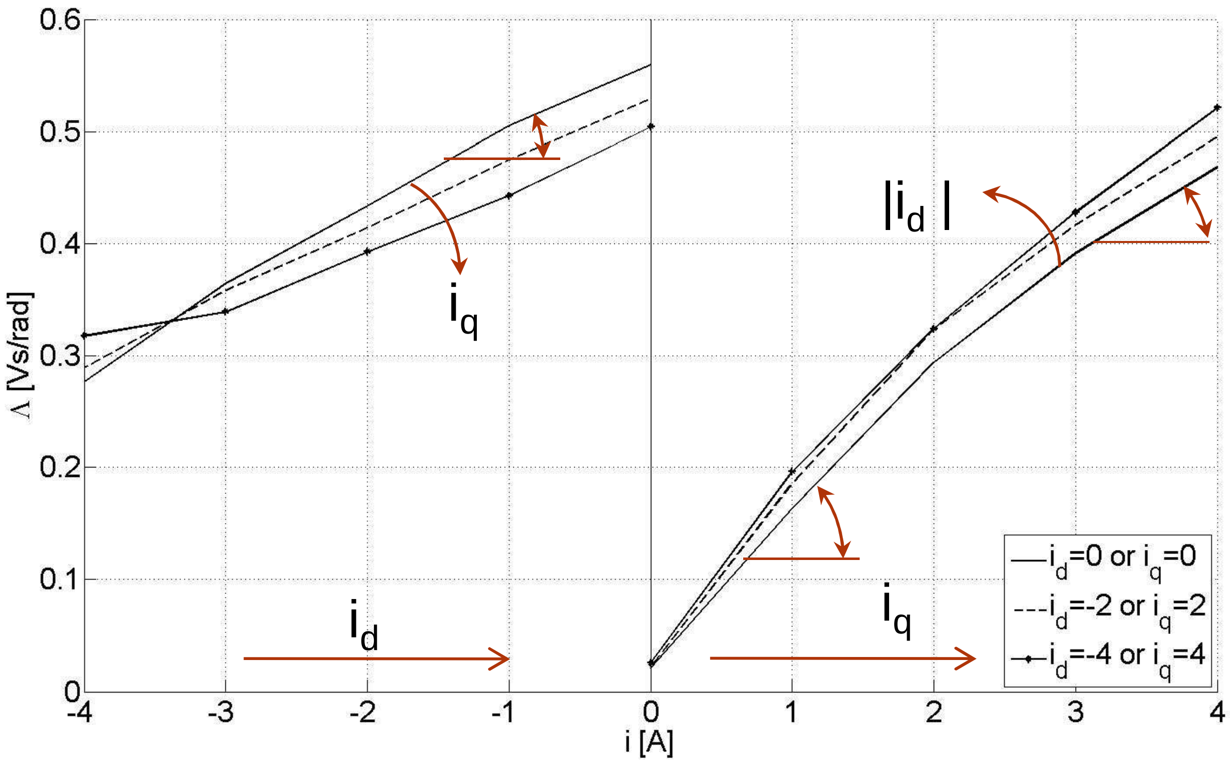
It has iron teeth between the poles

Inter-pole iron teeth increase quadrature inductance

Inset PM rotor

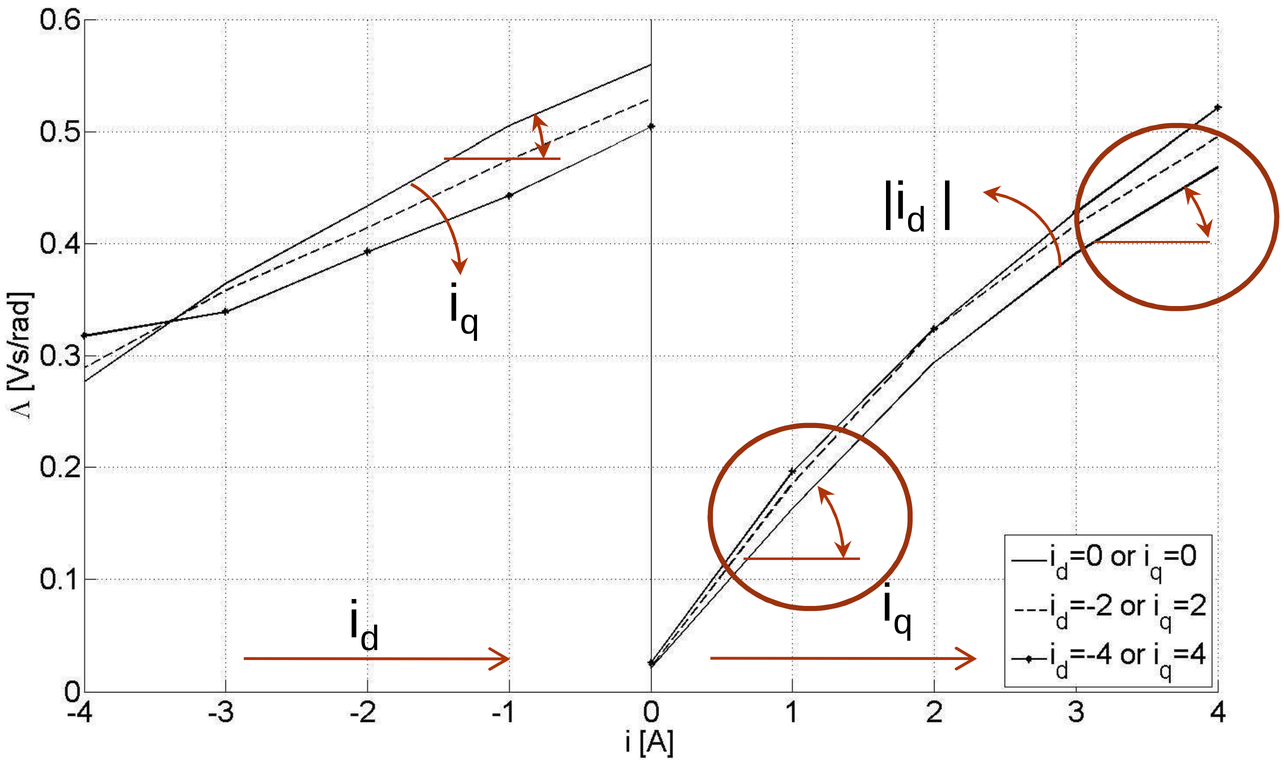


Inset PM rotor



Measured DC current-flux characteristics of an Inset PM motor. >>> Magnetic behaviour is not linear

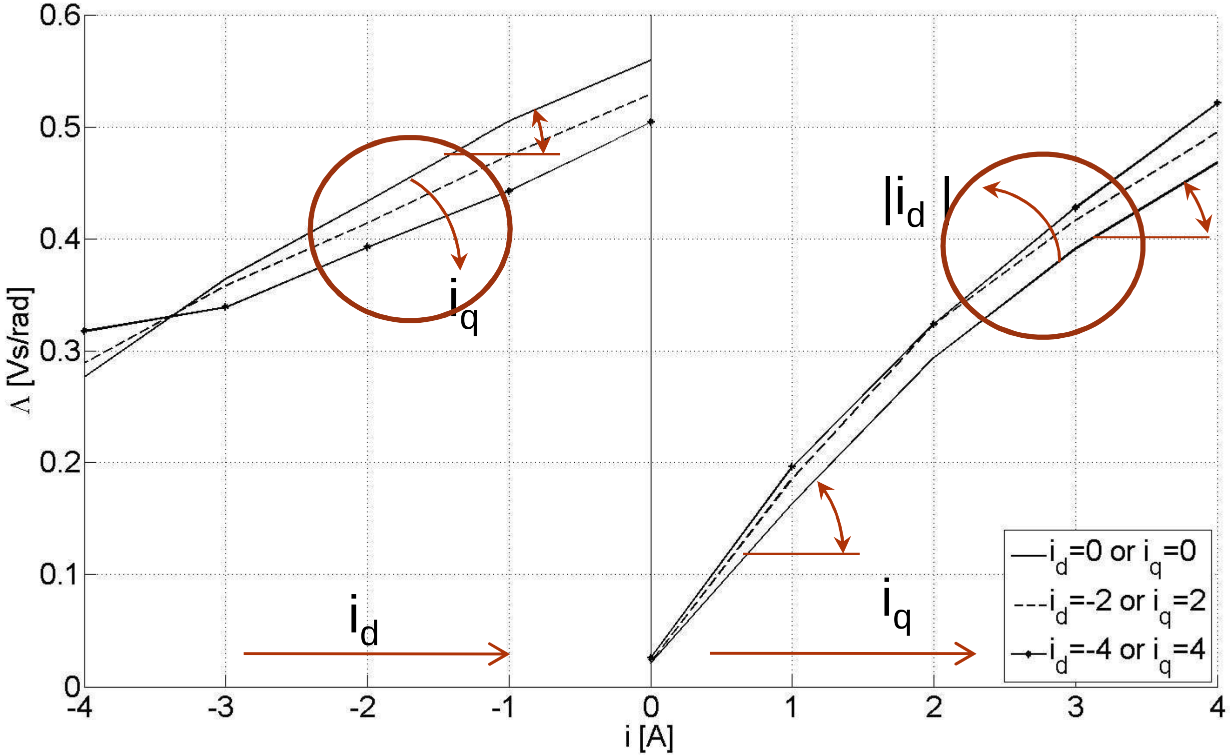
Inset PM rotor



Differential inductances have to be defined.

They change with the current level ….

Inset PM rotor



… and there are mutual inductances.

Inset PM rotor

In case of non-linear magnetic motors it results:

$$i_{hq}^{r} = -\frac{U_{hd}}{\omega_h}\left(\frac{l_\Delta \sin 2\Delta\theta + l_M \cos 2\Delta\theta}{l_d l_q - l_M^2}\right)\sin\omega_h t$$

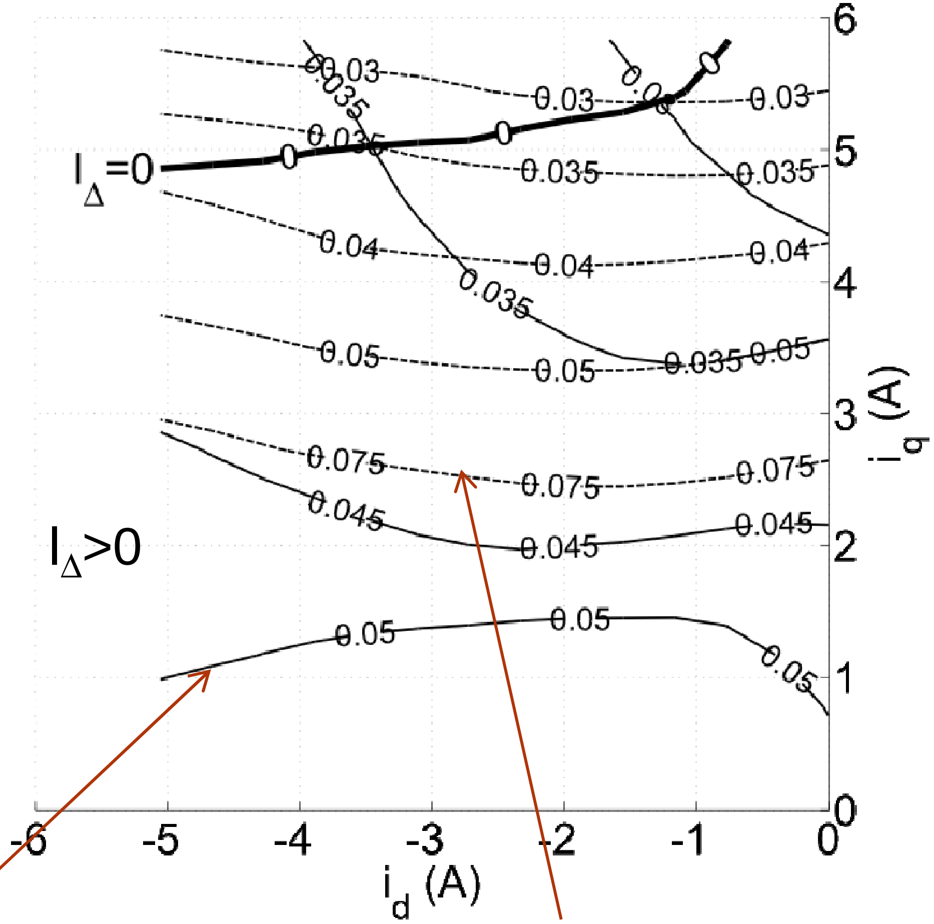
Nullify q-current a position error occurs:

$$\Delta\theta = \frac{1}{2}arctan\left(-\frac{l_M}{l_\Delta}\right)$$

Inset PM rotor

$$l_d = \frac{\partial \lambda_d(i_d, i_q)}{\partial i_d}$$

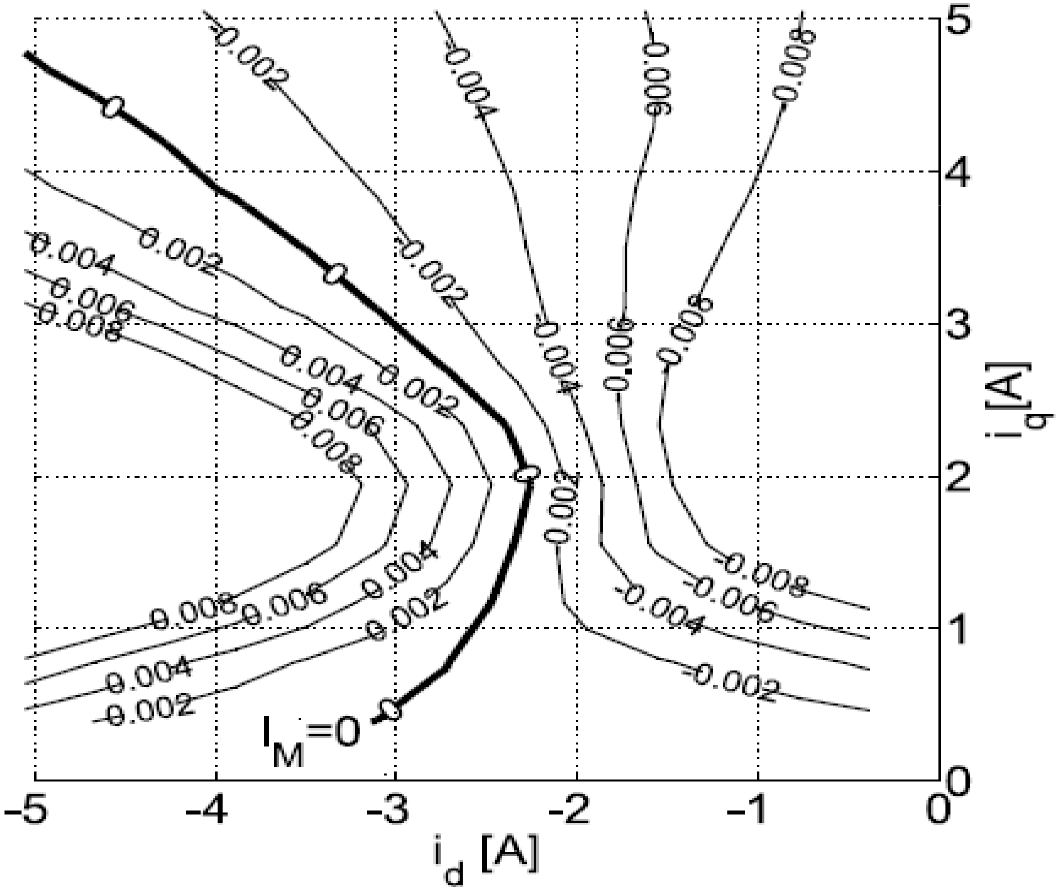
$$l_q = \frac{\partial \lambda_q(i_d, i_q)}{\partial i_q}$$



Loci of constant direct (solid line) and quadrature (dashed line) differential inductance of an Inset PM motor

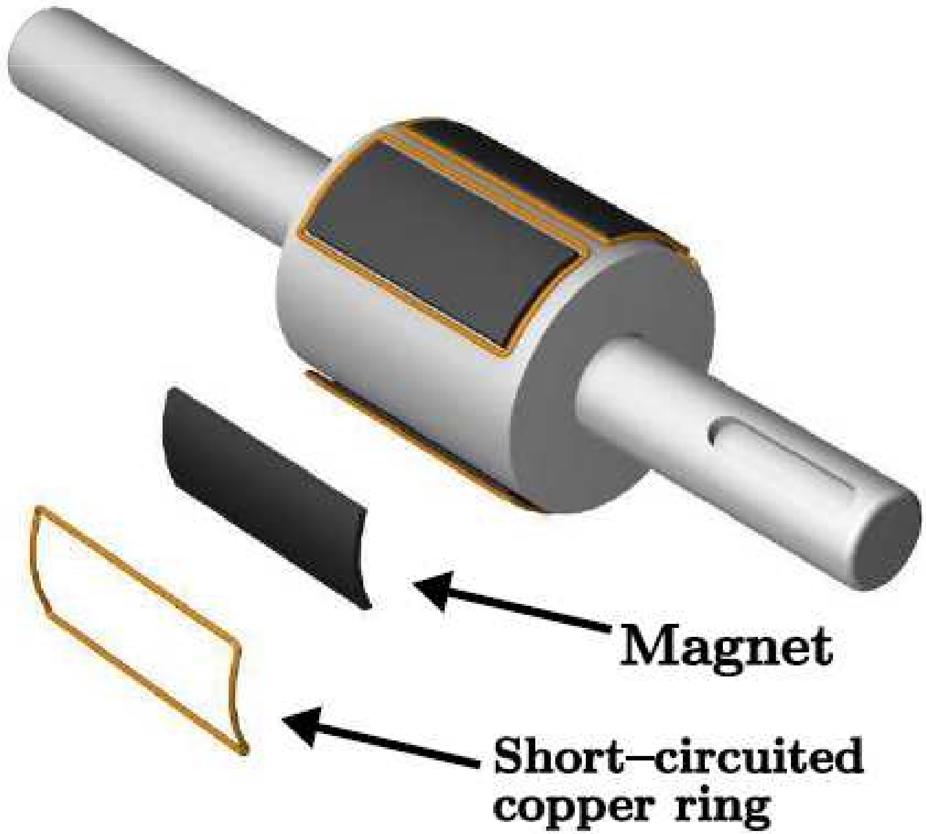
Inset PM rotor

$$l_M = \frac{\partial \lambda_d(i_d, i_q)}{\partial i_q} = \frac{\partial \lambda_q(i_d, i_q)}{\partial i_d}$$



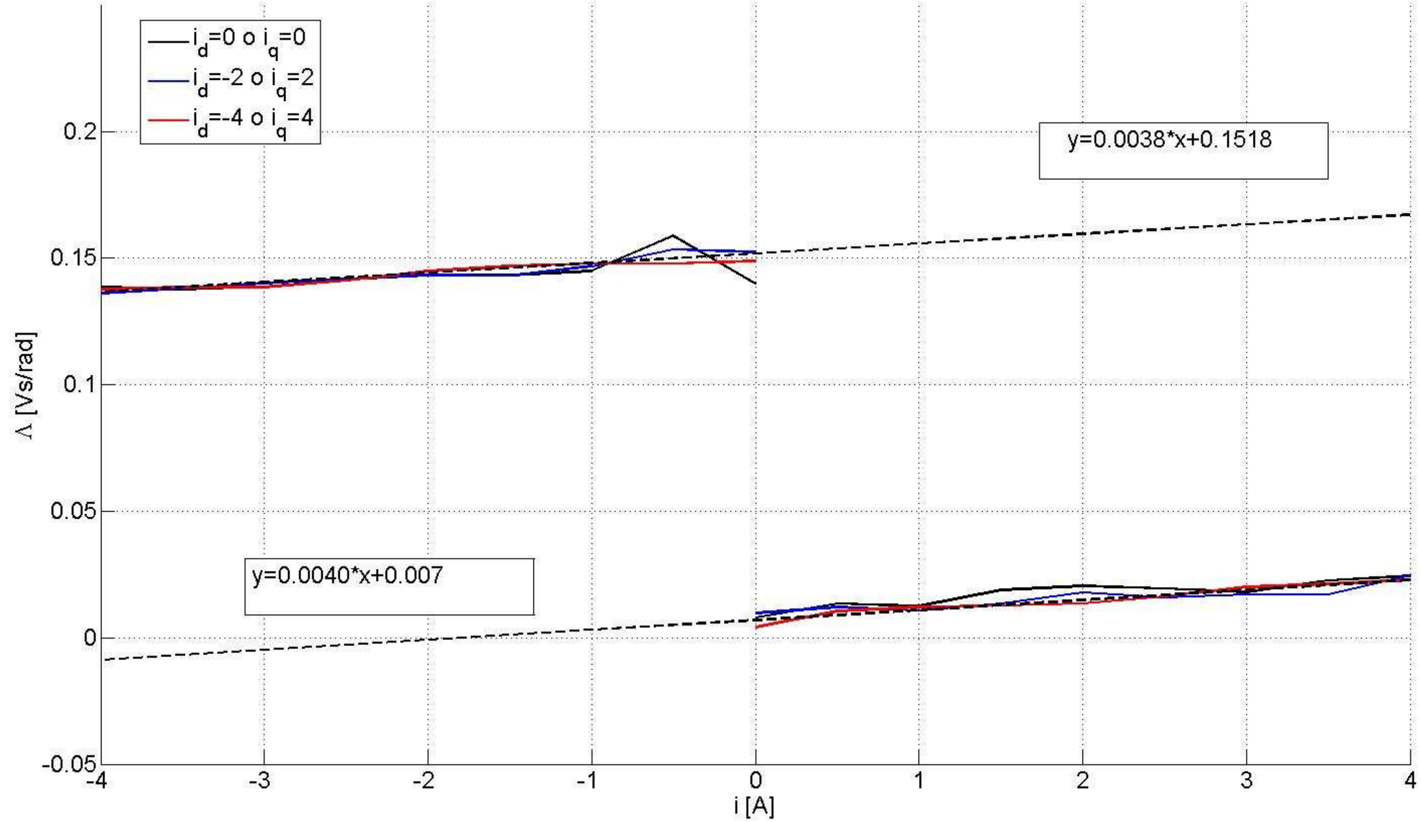
Loci of constant mutual differential inductance of an Inset PM rotor.

Ringed-pole SPM rotor



Ringed-pole SPM rotor

Ringed-pole SPM rotor



Measured DC current-flux characteristics of an Ringed-pole SPM motor. >>> <u>Magnetic behaviour is linear.</u>

Ringed-pole SPM rotor

- Motor equations are:

$$
\begin{aligned}
u_d &= R_s i_d + L_s \frac{di_d}{dt} + \mathbf{L_M} \frac{\mathbf{di_r}}{\mathbf{dt}} - \omega_{me} L_s i_q \\
u_q &= R_s i_q + L_s \frac{di_q}{dt} + \\
&\quad + \omega_{me} (L_s i_d + \mathbf{L_M i_r} + \Lambda_{mg}) \\
\mathbf{0} &= \mathbf{R_r i_r} + \mathbf{L_r} \frac{\mathbf{di_r}}{\mathbf{dt}} + \mathbf{L_M} \frac{\mathbf{di_d}}{\mathbf{dt}}
\end{aligned}
$$

- By solving at hf the d- and q-axis show different hf impedences given by:

Ringed-pole SPM rotor

$$\dot{Z}_d(\omega_h) = \frac{\overline{U}_d(\omega_h)}{\overline{I}_d(\omega_h)} = \frac{j\omega_h L_s}{\dot{\xi}(\omega_h)}$$

$$\dot{Z}_q(\omega_h) = \frac{\overline{U}_q(\omega_h)}{\overline{I}_q(\omega_h)} = j\omega_h L_s$$

where

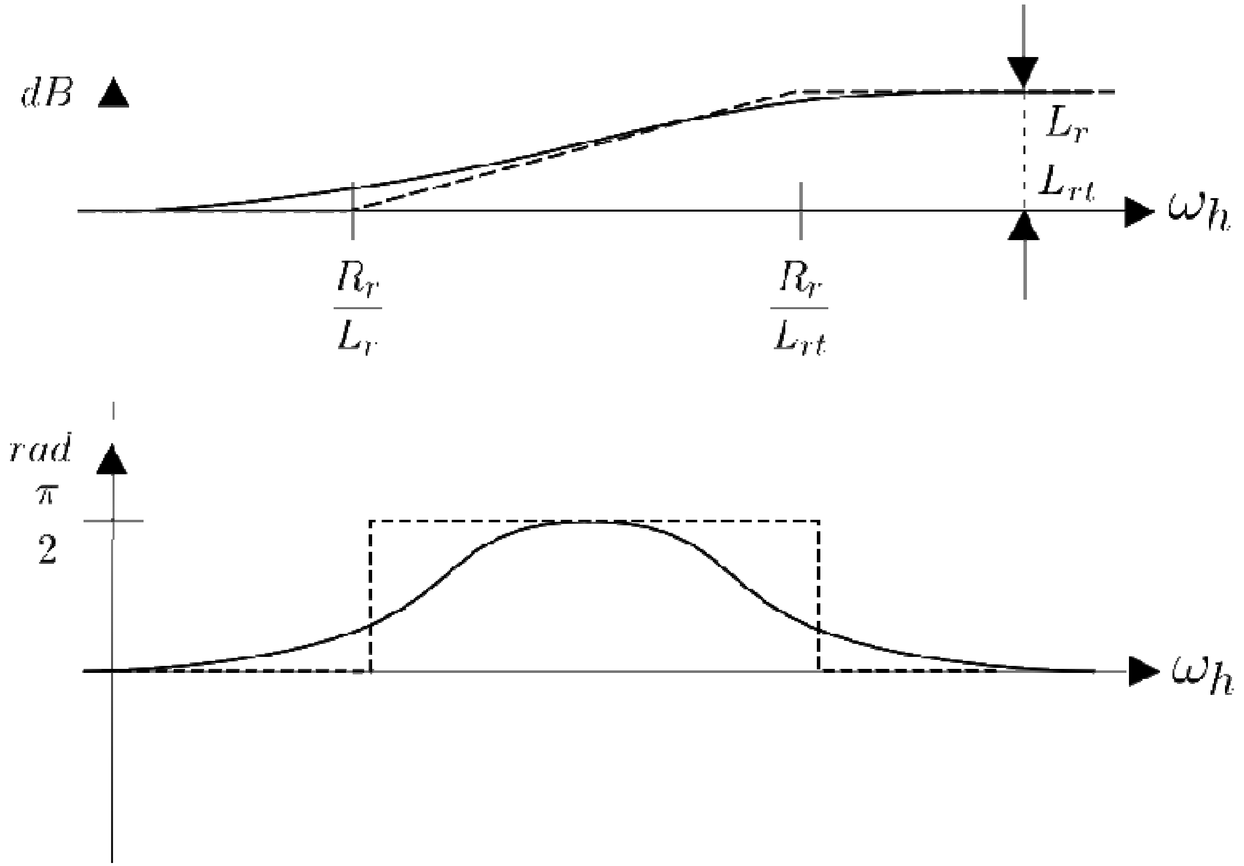
$$\dot{\xi}(\omega_h) = \frac{\dot{Z}_q(\omega_h)}{\dot{Z}_d(\omega_h)} = \frac{R_r + j\omega_h L_r}{R_r + j\omega_h L_{rt}}$$

is the high frequency saliency and

$$L_{rt} = L_r - \frac{L_M^2}{L_s}$$

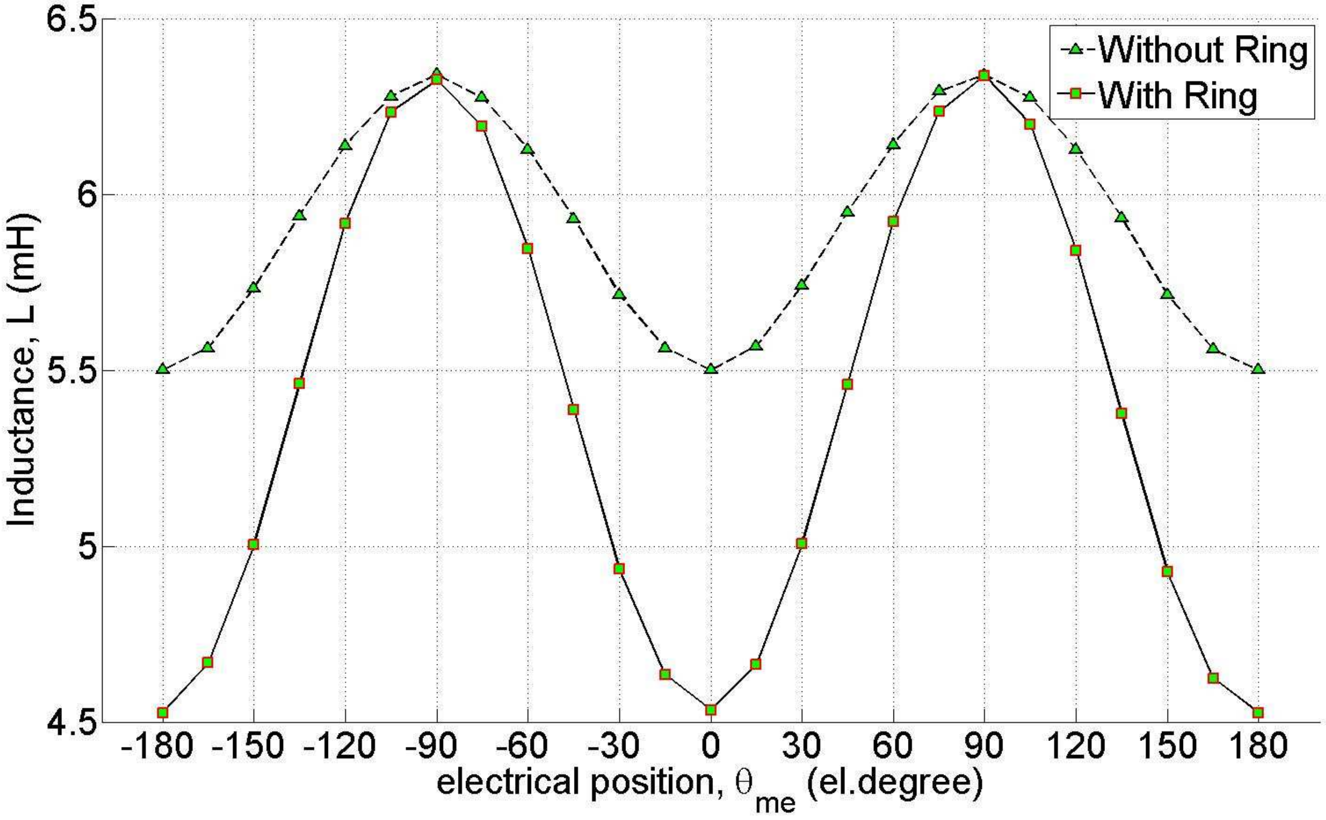
is the rotor transient inductance.

Ringed-pole SPM rotor



Frequency response of the hf saliency

Ringed-pole SPM rotor

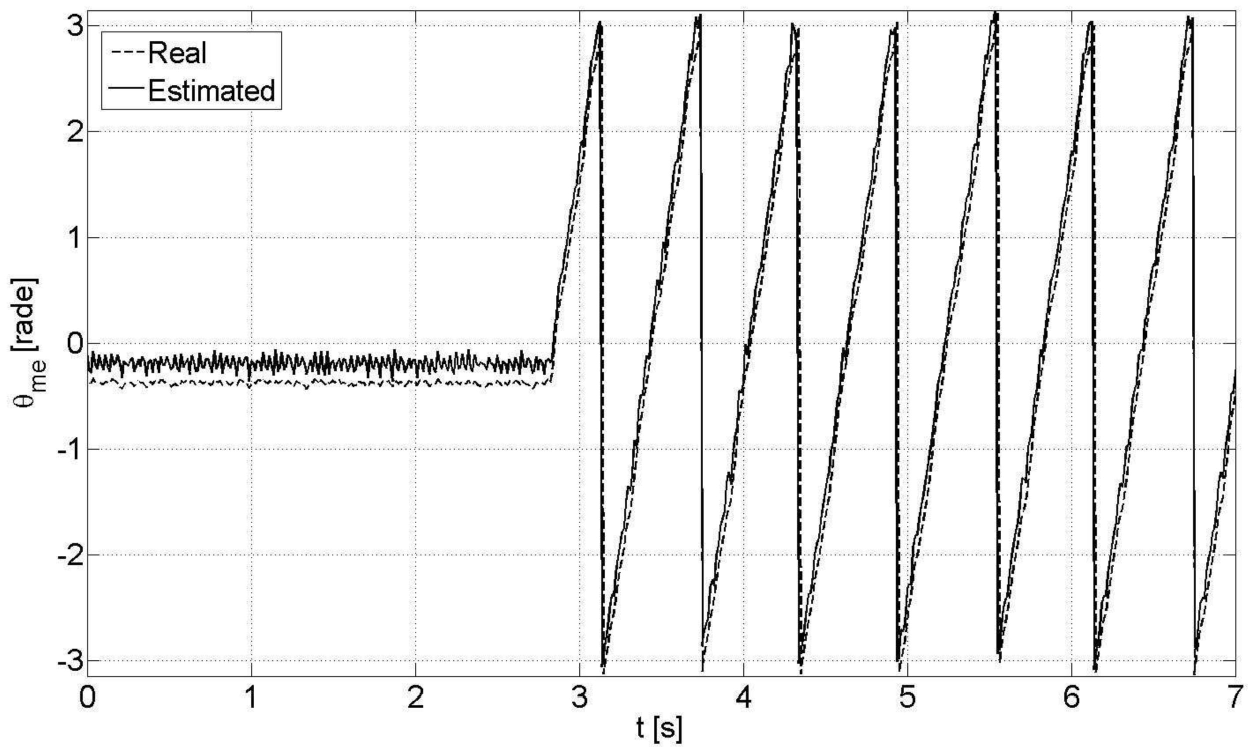


Phase-to-phase hf inductance.

Ringed-pole SPM rotor

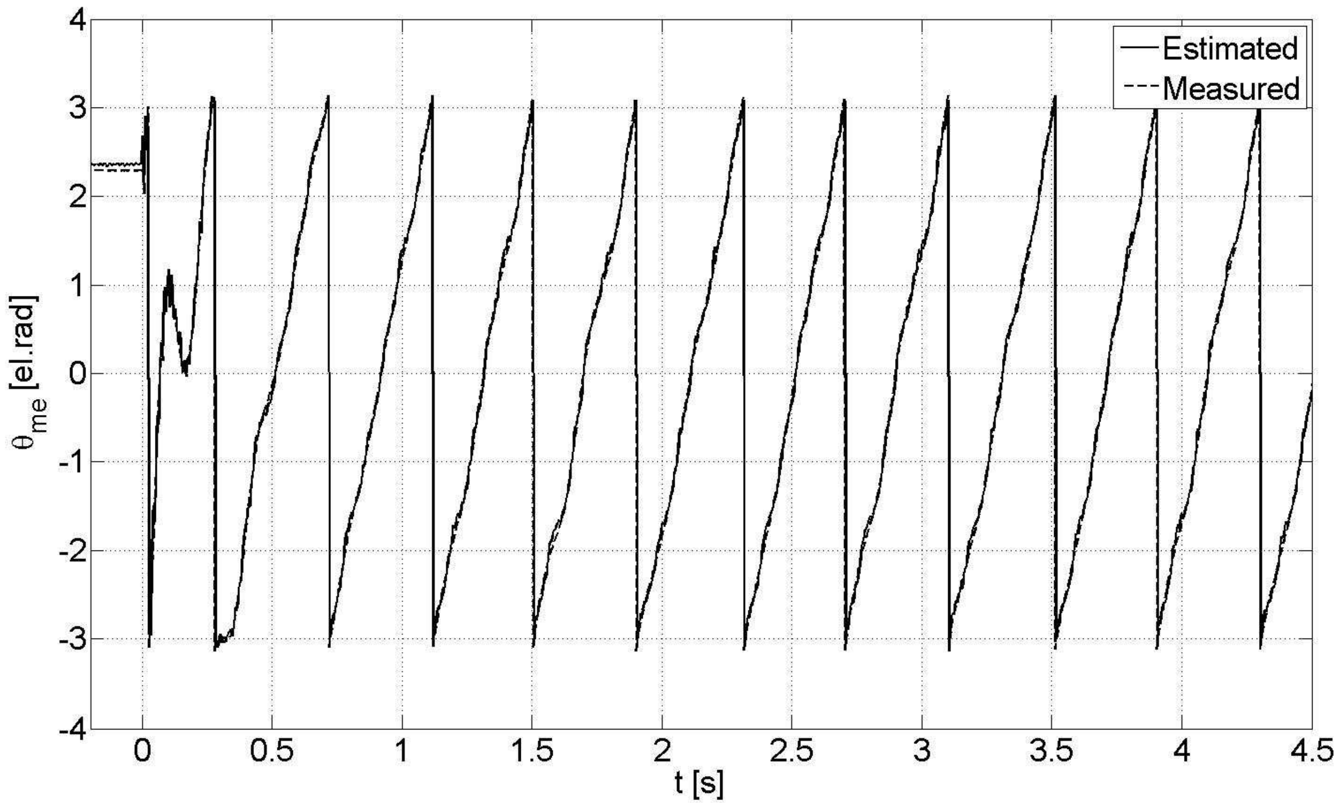
- The ring does not affect d-q (DC) operation;
- Additional losses are negligible (fractions of watts);
- Sensorless operation is not affected by load conditions

Test results



- Experimental results for Inset PM motor
  - Estimated and measured rotor position

Test results



- Experimental results for Ringed-pole PM motor
  - Estimated and measured rotor position

Conclusions

- The paper describes two modified SPM rotor configurations designed to allow rotor position sensorless detection at low speed and at stanstill. By hf voltage injection.

- Experimental test results find out on motor prototypes have been also described and confirm the effectiveness of the proposed rotor design

- Simple d-q control possibilities of the modified motors preserved.