Encoderless Control of AC Drives Recent Achievements – Realistic and Unrealistic Expectations

Ralph M. Kennel, Technische Universitaet Muenchen, Germany
kennel@ieee.org

Reasons for Industrial Applications of Drives with encoderless Control:

- Cost ?? ✋ ??
- Reliability
- Robustness

is encoderless (sensorless) 👍 ✓ resulting in additional cost ???

👍 ✓

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Industrial Drives with Sensorless Control

since several years / decades sensorless control is investigated

and published on conferences and magazines

- **acceptance** in industry, however, is rather **low**

Why ?

new ideas and concepts are interesting for industry,

only if they do **not** result in higher cost or higher effort!!!

What does that mean

for industrial drives with sensorless control ?

- ☐ no additional or more powerful processors / controlle
- ☐ no additional hardware or additional sensors (e. g
- ☐ no increased installation effort with respect to para

this was valid from 2000 to 2010

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Why ?

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only if they do **not** result in higher cost or higher effort!!!

What does that mean

for industrial drives with sensorless control ?

- ☐ single scheme for wide speed range (no phase over)
- ☐ no additional noise (except usual noise by inverter)
- ☐ insensitivity with respect to parameter variations

What does industry think today ?

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Industrial Drives with Sensorless Control

Actual Requirements from Industry

- there should be a single concept for encoderless control
  for the complete speed range (from standstill to maximum speed)

  ☑ single scheme for wide speed range (no phase over)

- in case there is a signal to be injected for speed/position detection
  this should not cause any additional noise
  - except usual noise caused by inverter supply with standard PWM

  ☑ no additional noise

- parameters of electrical machine and/or power elctronics should not impact
  the performance of encoderless control too much (a certain impact is acceptable)

  ☑ insensitivity with respect to parameter variations

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Sensorless (Encoderless) Motor Drives

introduction

- fundamental model methods
- high frequency injection methods

encoderless control of synchronous machines

- machine response on high frequency injection voltages
- tracking of magnetic saliencies / anisotropies

practical results

- experiences with industrial drives
- ... what about “predictive” encoderless control ?
- ... what about arbitrary injection ?
- use of current derivation sensors ?
- experiences with different motor designs

conclusions

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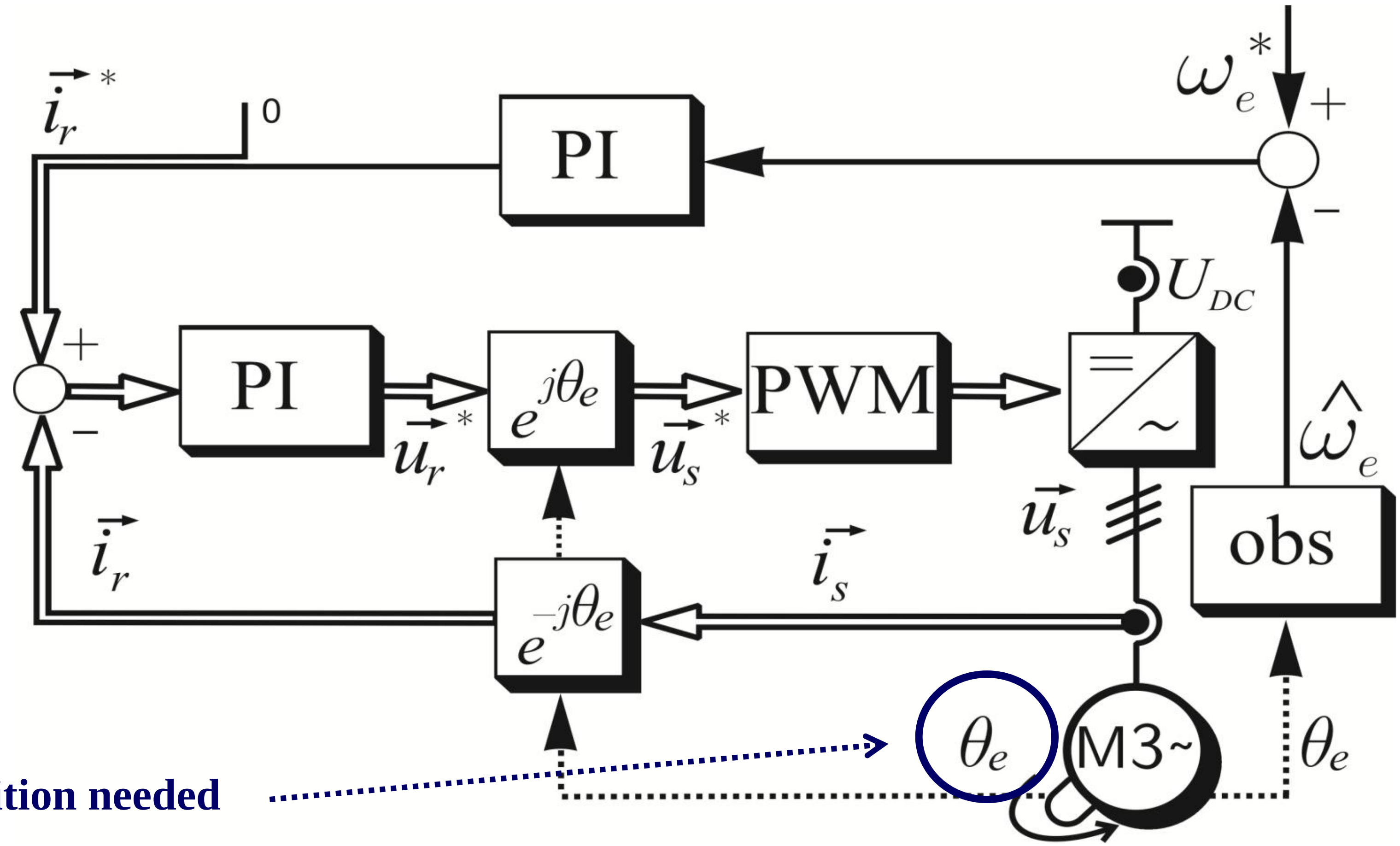
Field oriented control of PMSM



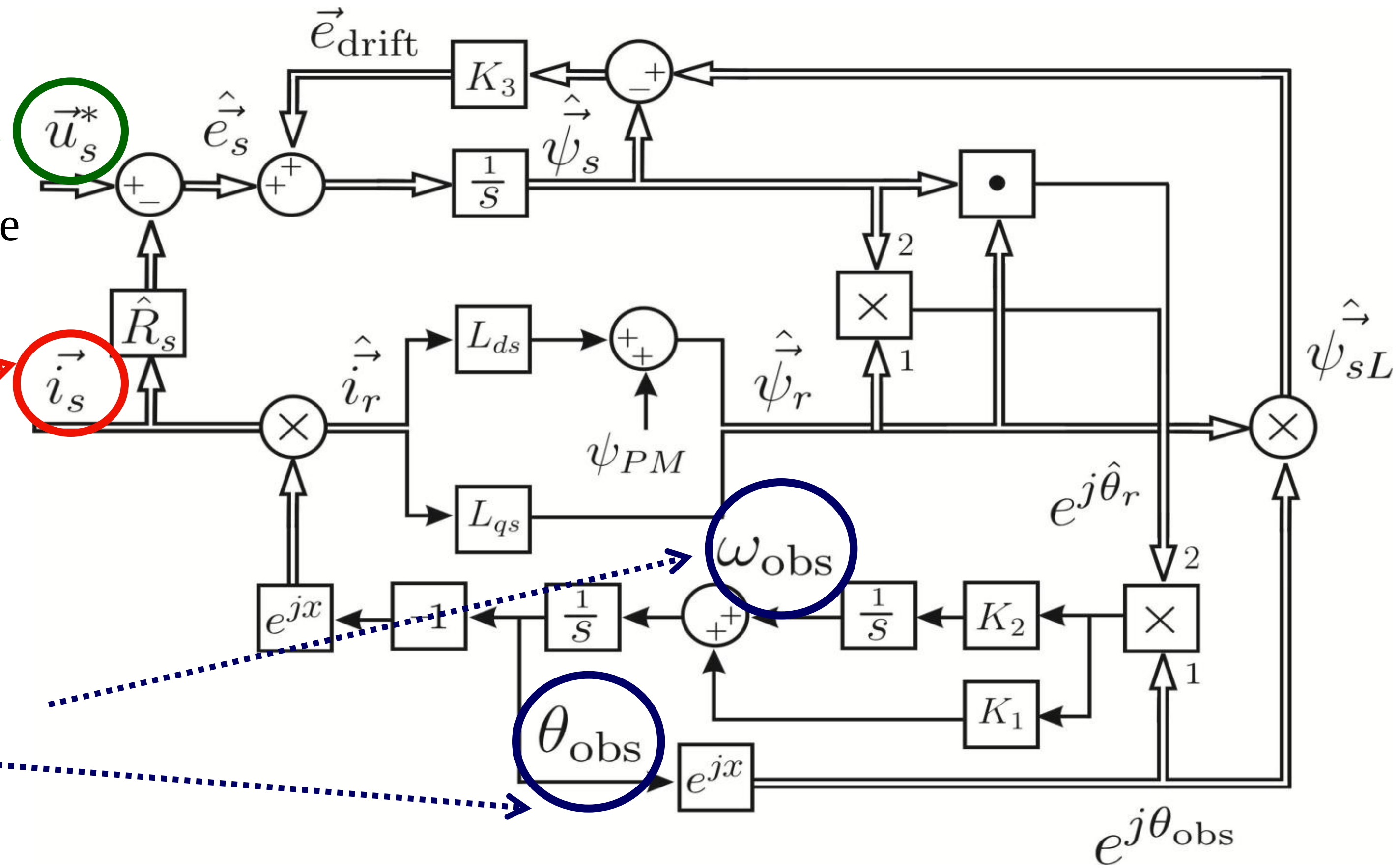
rotor position needed

Fundamental model based position estimation

when knowing voltage

as well as current

it is possible to
estimate rotor speed
and rotor position



Calculation of Speed by Fundamental Model is not Practicable for Very Low Speeds

... because

- the voltage signal becomes very small
- errors between real voltage and values used for calculation

  cannot be avoided and become more significant
- DC components of these errors

  let the integrators for flux calculation drift away

  → the calculated speed gets more and more incorrect

is an encoder/resolver the only feasable solution ??

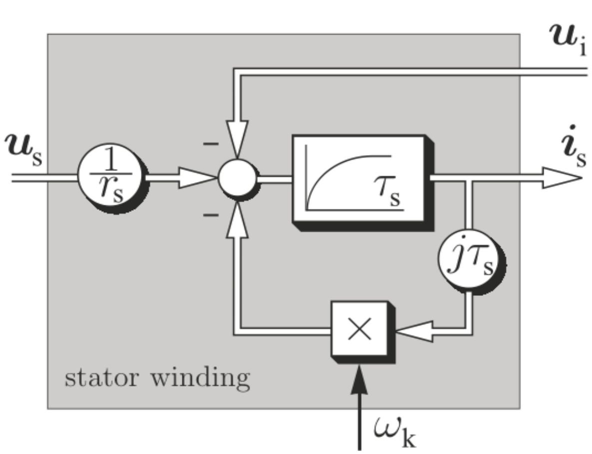
Categories of Machine Models for „Sensorless“ Control

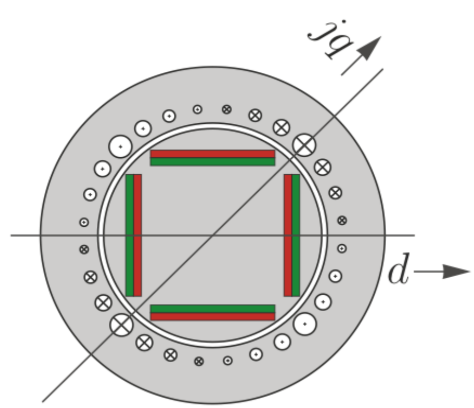
fundamental models

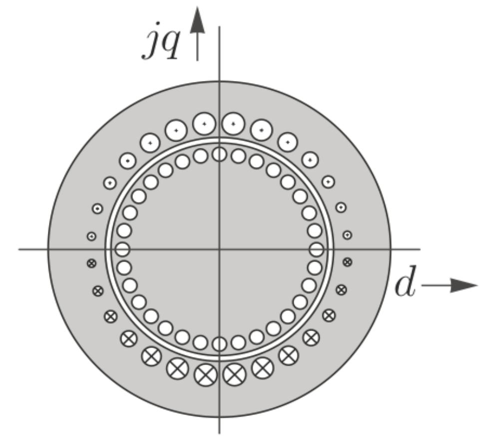
- EMF-models, observerer
- flux-modulation
- ...

models based on anisotropies

- dq-inductance
- rotor slotting-effects
- main field saturation
- ...







fundamental model

- simple realisation
- does not work at frequency 0
- parameter dependencies

high frequency injection

current injection

- measuring voltage is high enough
- additional voltage sensors

voltage injection

transient current response

- no additional hardware
- very short measuring time

stationary current response

- standard microcontroller sufficient
- very small measuring current

INFORM method

according to M. Schroedl

(Technical University of Vienna, Austria)

- this is basically a transient voltage injection method
  → currents have to be sensed at specific times !!!
- when using standard current transducers
  → these cannot be synchronized with PWM

→ the hardware of a standard industrial drive
has to be changed

nevertheless this method comes close to industrial needs !

Stationary Signal Injection Methods

according to R. Lorenz, S.-K. Sul, R. Kennel, etc.

- the basic idea is

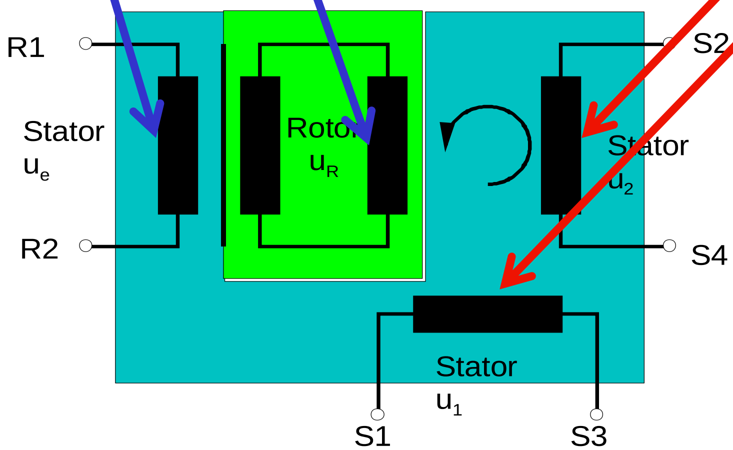
  to use the electrical machine itself as a resolver !!!

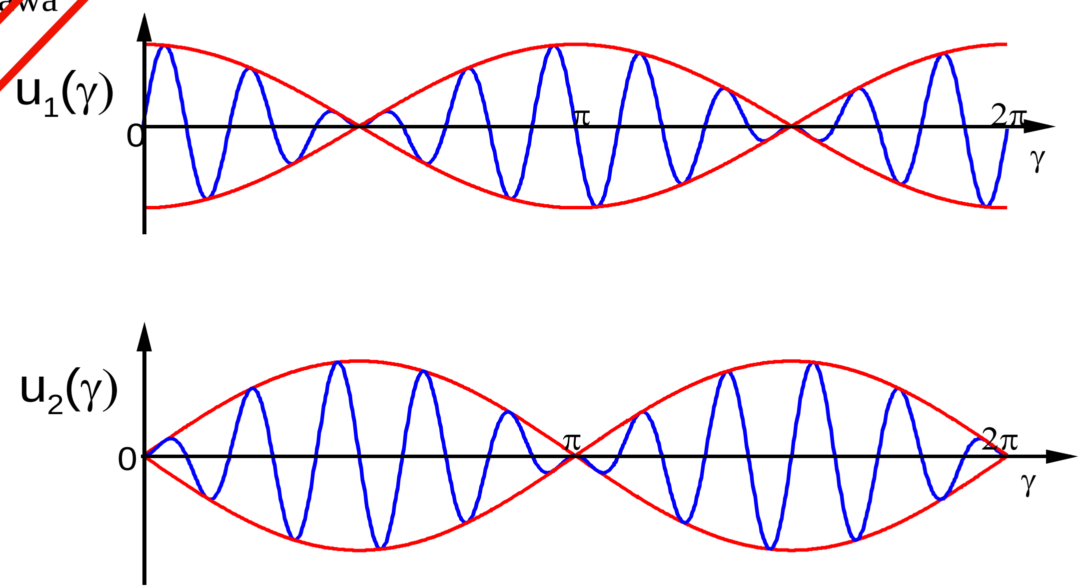
Resolver

injection of a stationary (sinusoidal) high frequency signal

sensing of a two-dimensional stationary (sinusoidal) signal response

Tamagawa





Stationary Signal Injection Methods

according to R. Lorenz, S.-K. Sul, R. Kennel, etc.

- the basic idea is

  to use the electrical machine itself as a resolver !!!

- a resolver is nothing else but an electrical machine

  → can we operate the motor itself like a resolver ?

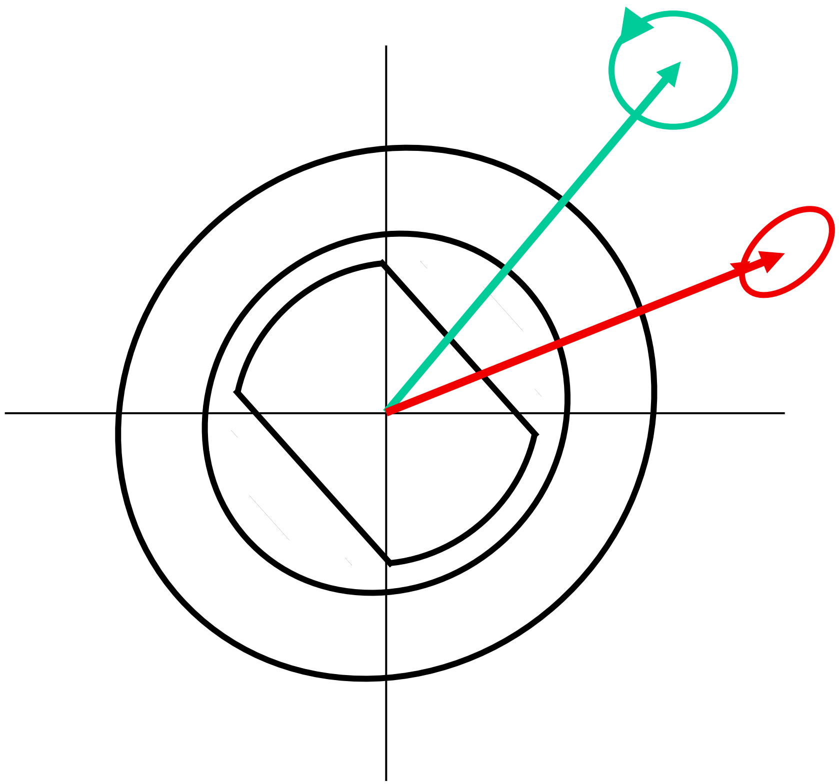
- if the machine itself is a resolver (encoder)

  → is that really an „encoderless“ control ???

now we do the same with an electrical AC machine

→

injection of high frequency voltages



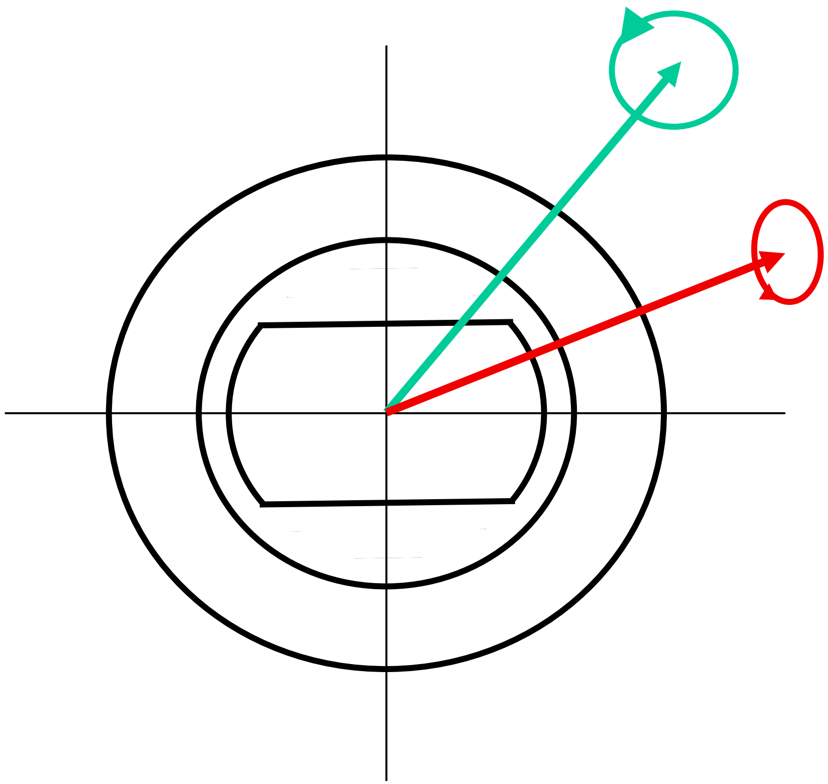
fundamental voltage phasor/vector

fundamental current phasor/vector

injected high frequency voltage phasor/vector

high frequency current phasor/vector (response)

injection of high frequency voltages



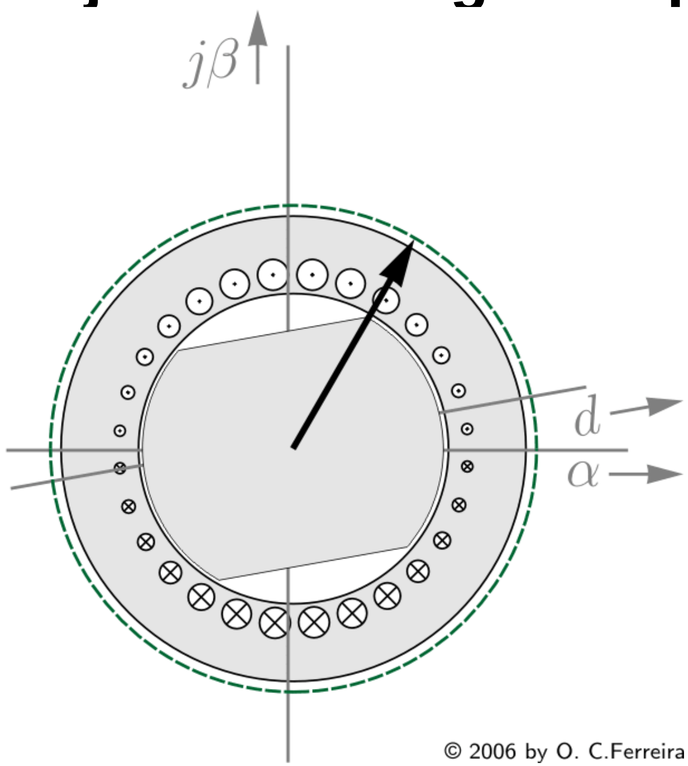
fundamental voltage phasor/vector

fundamental current phasor/vector

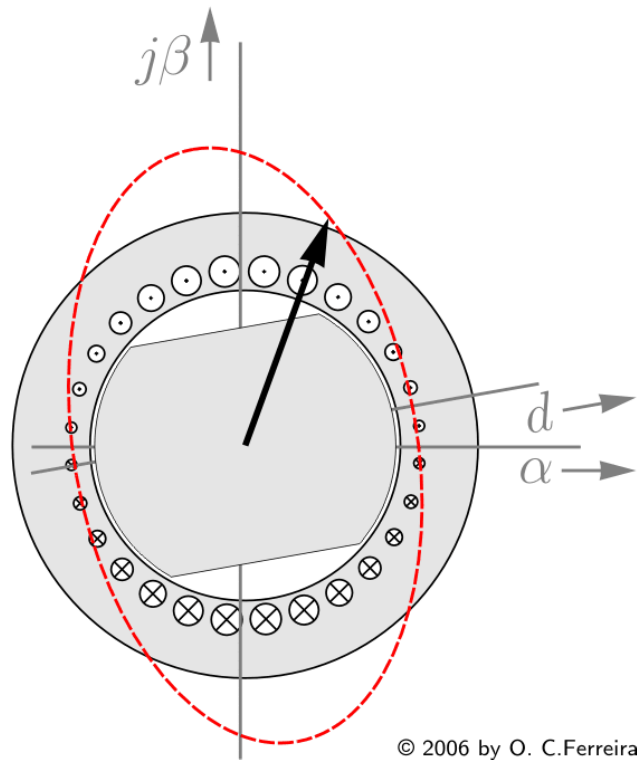
injected high frequency
voltage phasor/vector

high frequency
current phasor/vector (response)

Injection of High Frequency *Rotating* Phasors



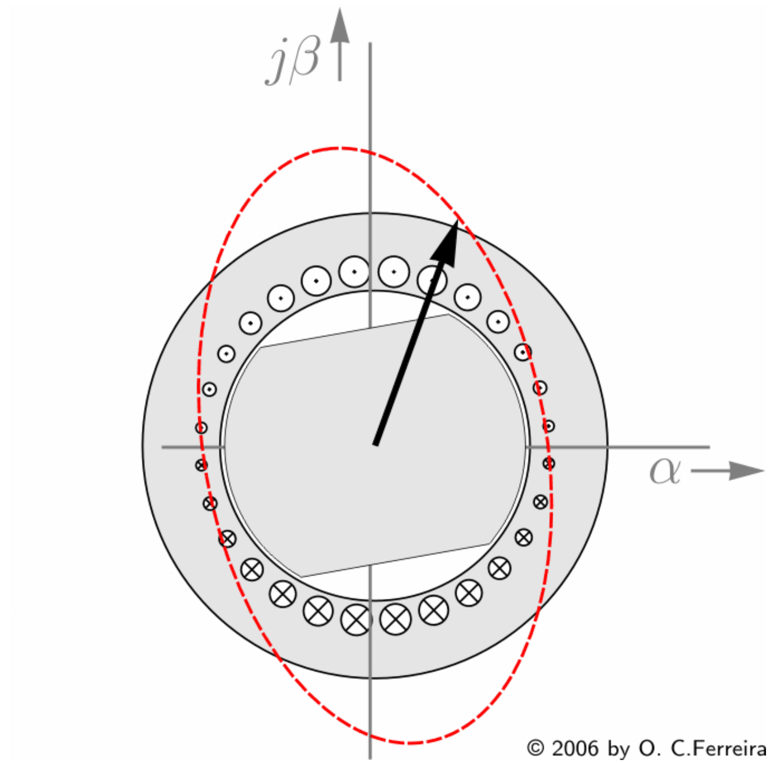
rotating voltage phasor $\boldsymbol{u}_c$



elliptic current response $\boldsymbol{i}_c$

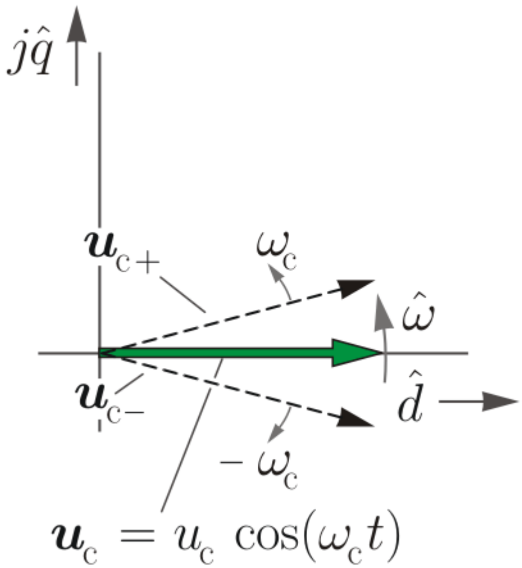
Position Information of Salient Rotors in High Frequency *Rotating* Phasors

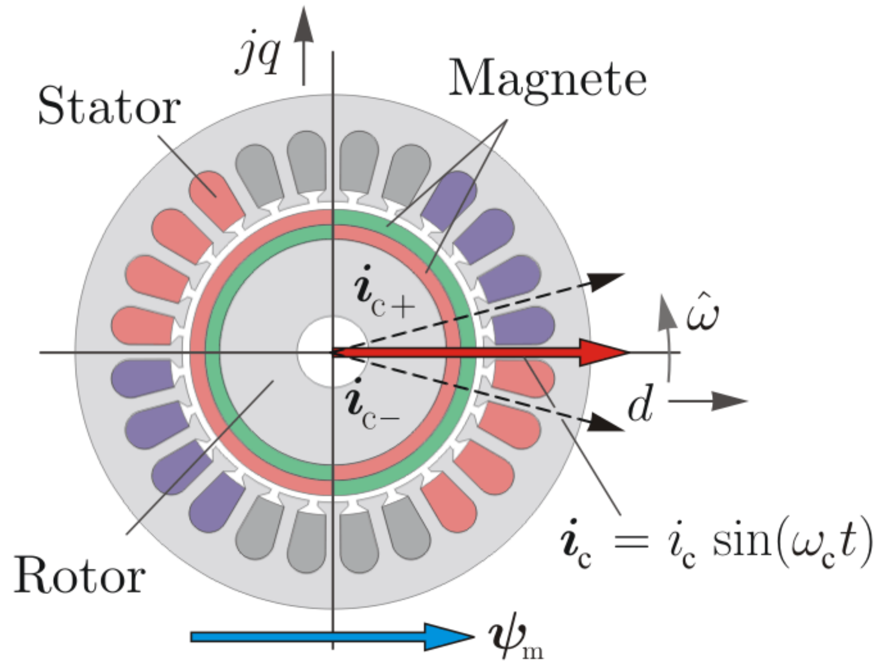
- machine responds
  on a rotating voltage phasor
  with an elliptic current response
- ellipse is correlated
  with the geometric anisotropy
  of the rotor
- rotor position information
  is included
  in the high frequency current



elliptic current response $\boldsymbol{i}_c$ (rotating)

Injection of High Frequency
Alternating (Pulsating) Voltage Phasors





composing an alternating (pulsating) voltage phasor
by two phasors rotating in opposite direction

advantage :
no rotational (HF) field
→ no additional torque

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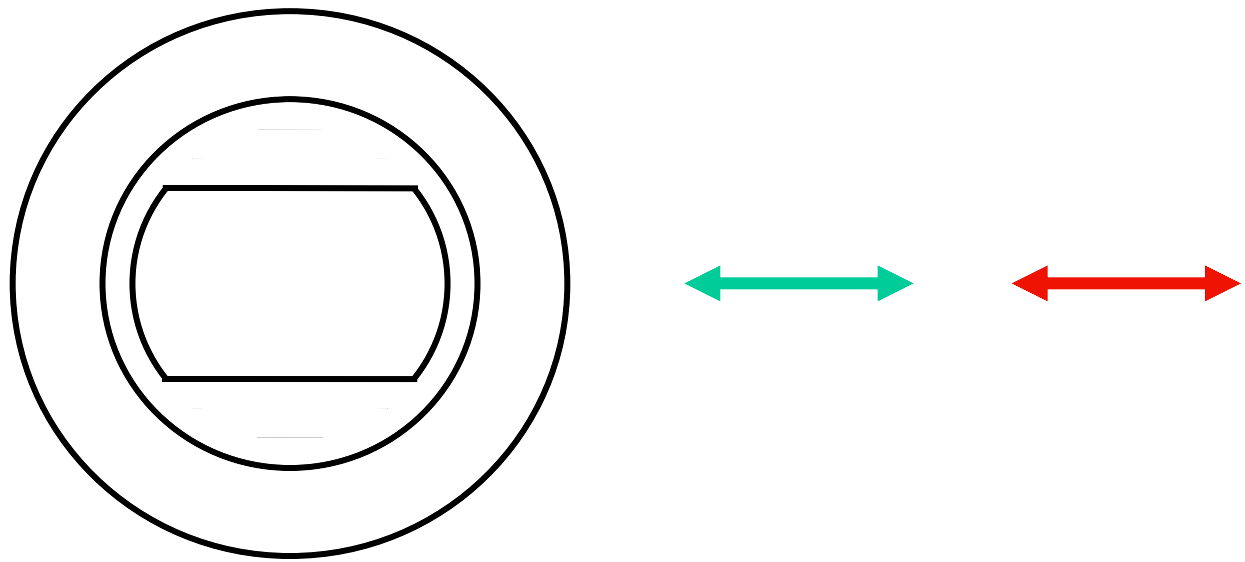
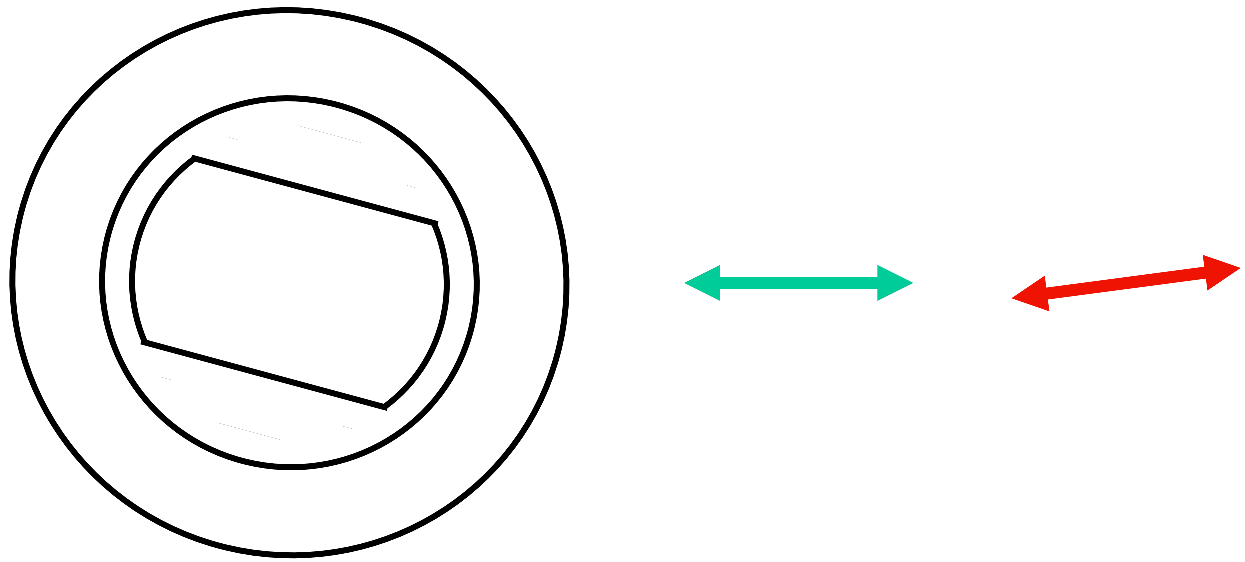
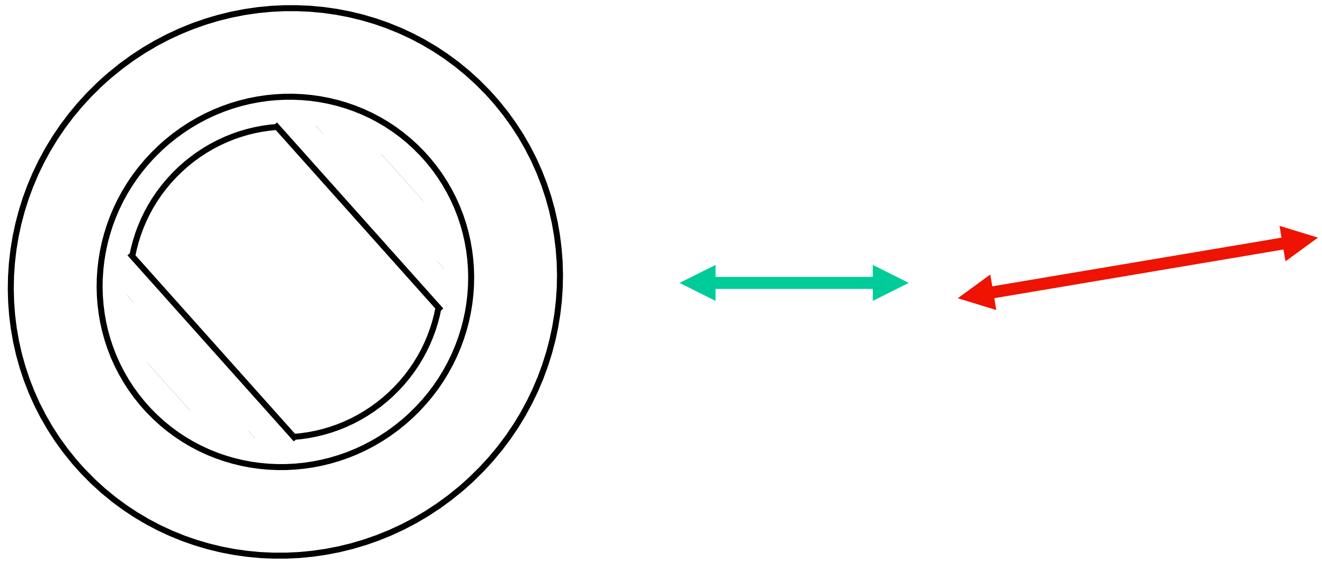
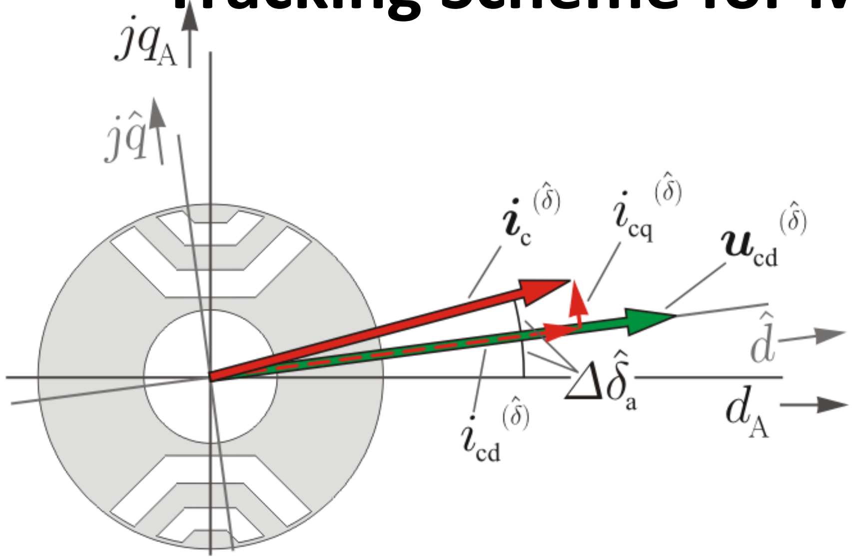
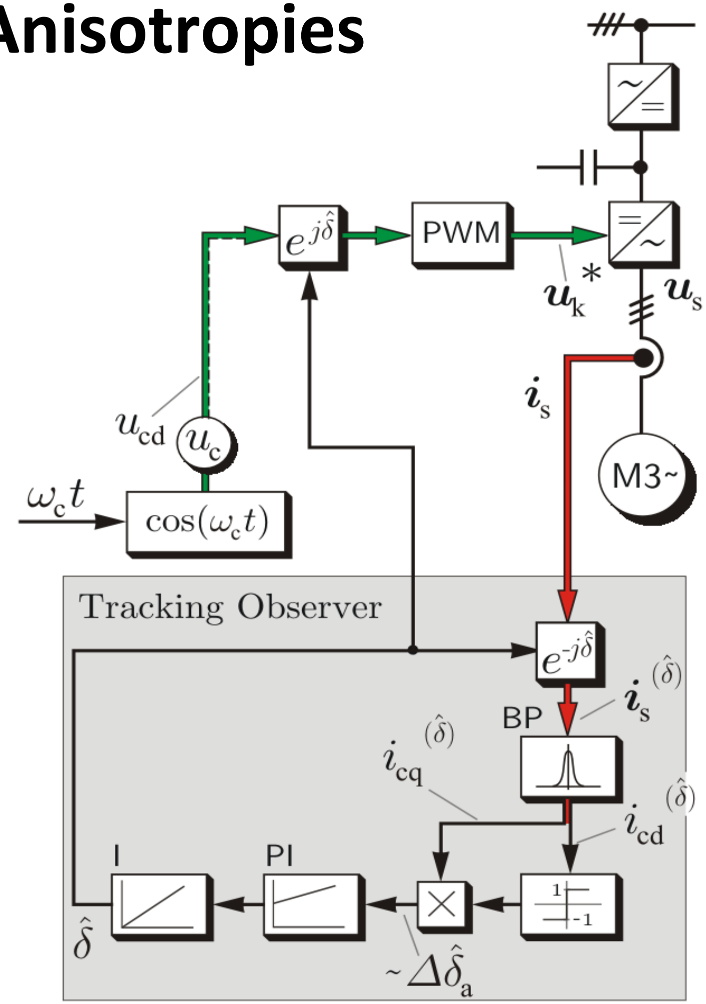






Tracking Scheme for Magnetic Anisotropies

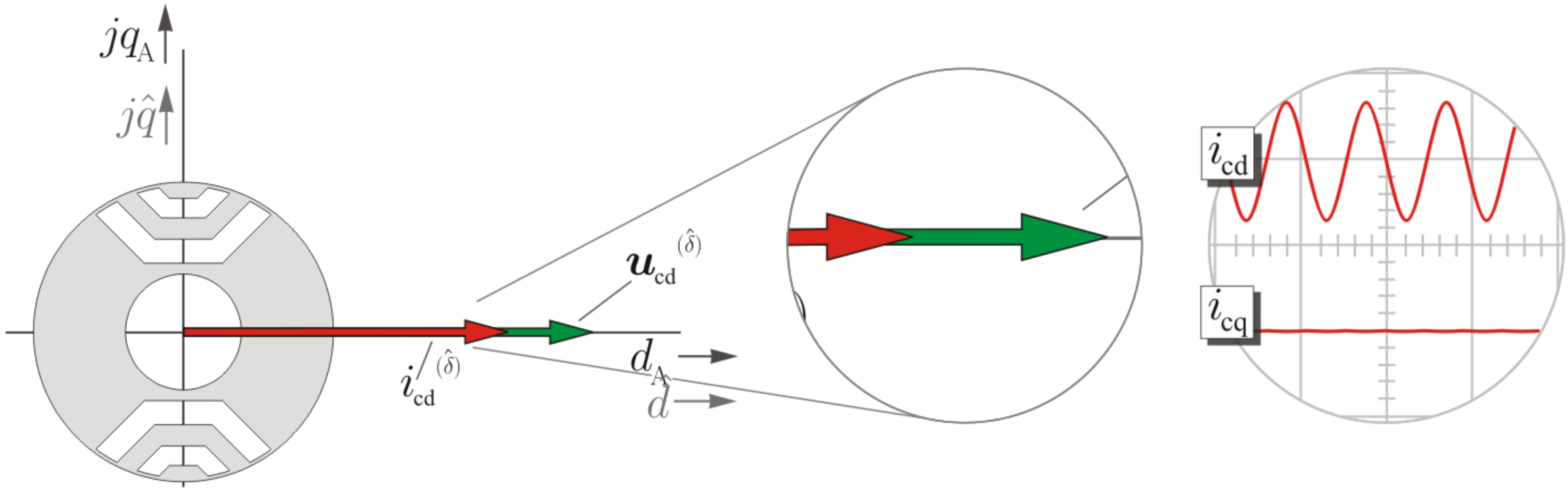




$$\boldsymbol{i}_{cd}^{(\hat{F})} = \mathrm{K}\cdot\sin(\omega_c t)\boldsymbol{l}_{cq}$$

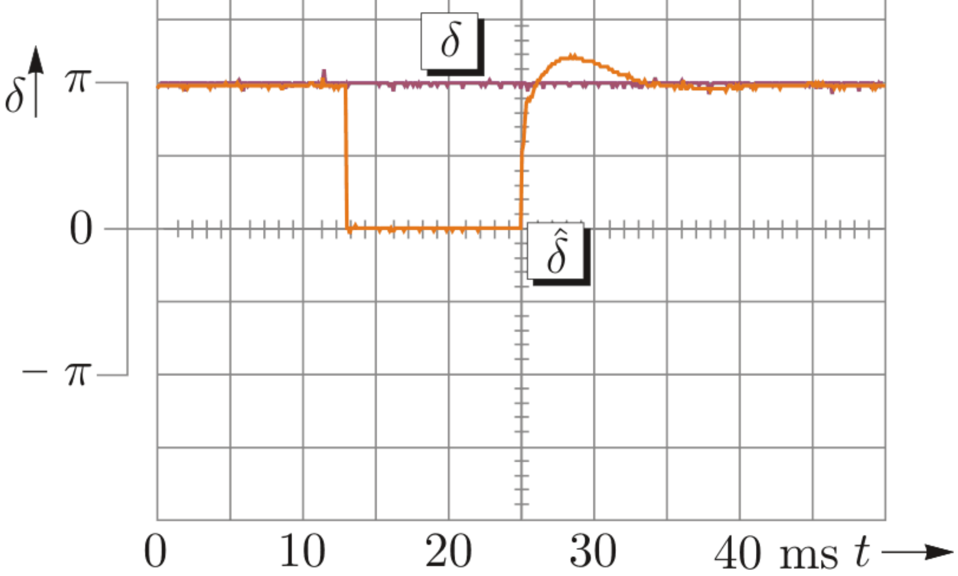
$$\boldsymbol{i}_{cq}^{(\hat{F})} = -\mathrm{K}\cdot\sin(\omega_c t)(\boldsymbol{l}_{cq} - \boldsymbol{l}_{cd})\Delta\hat{\delta}_a$$

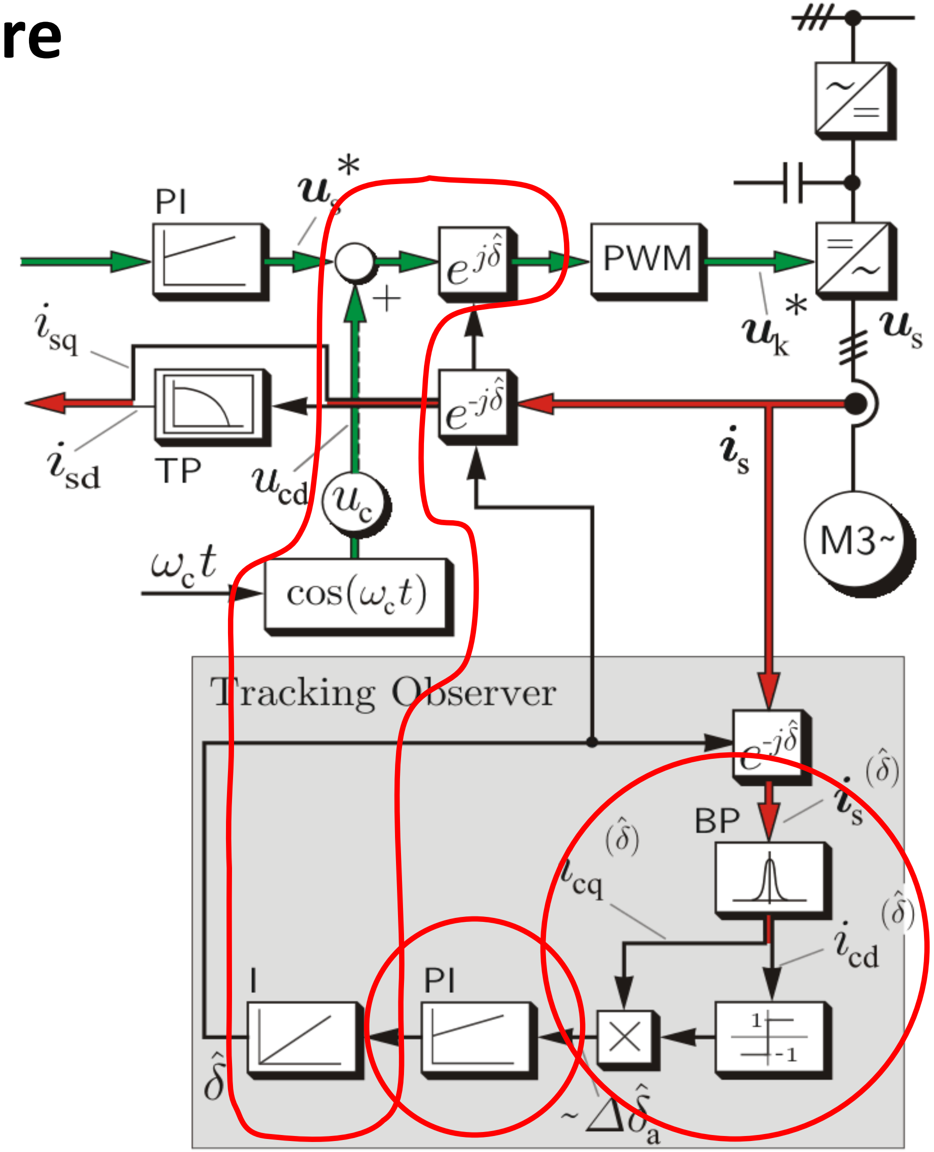
Tracking Scheme for Magnetic Anisotropies



Tracking the estimated angle of the rotor flux by controlling $\boldsymbol{i}_{cq}$ to 0

Encoderless Control Structure

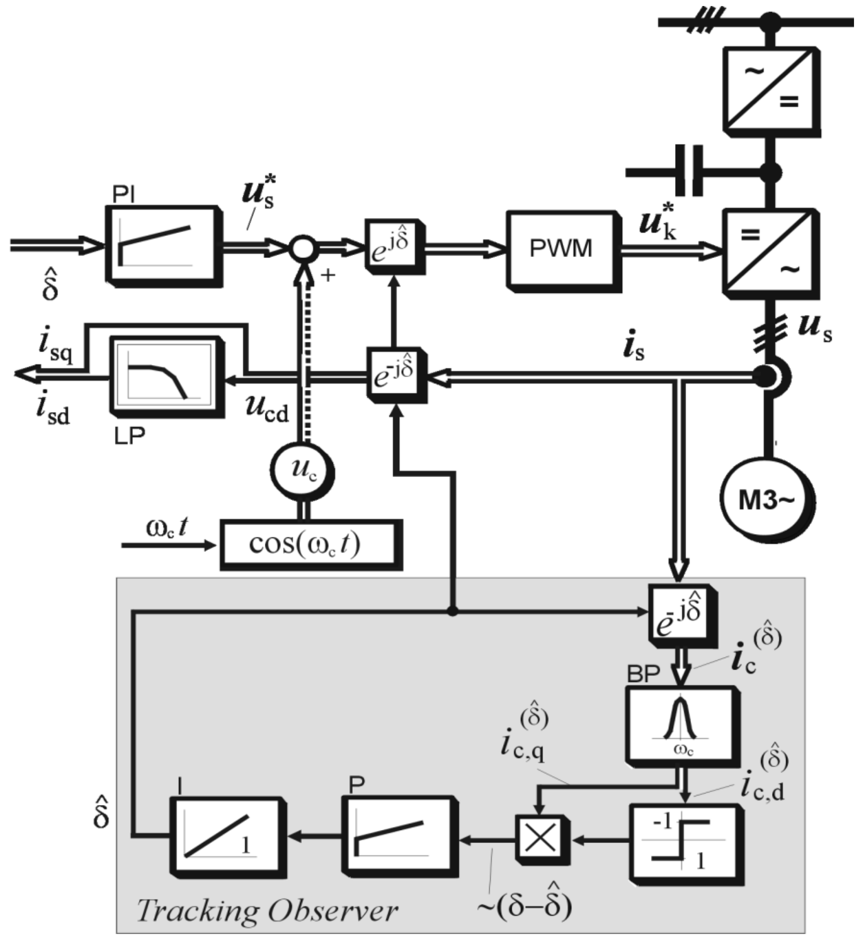




step response of the PLL;
PLL is locked after ca. 10 -15 ms

control structure

of an encoderless control
with alternating high frequency
signal injection

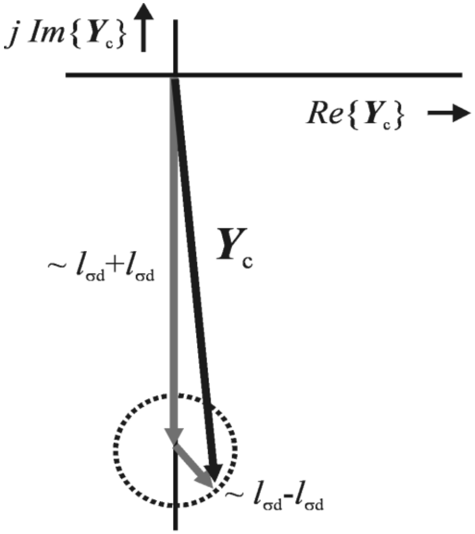


the estimated angle can be used

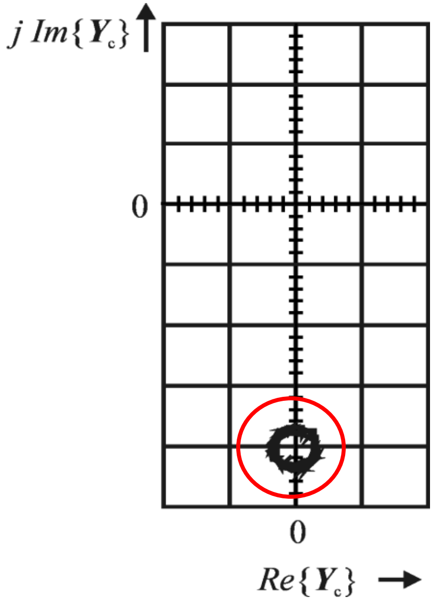
for *field orientation* as well as for

speed or *position control*

of synchronous machines

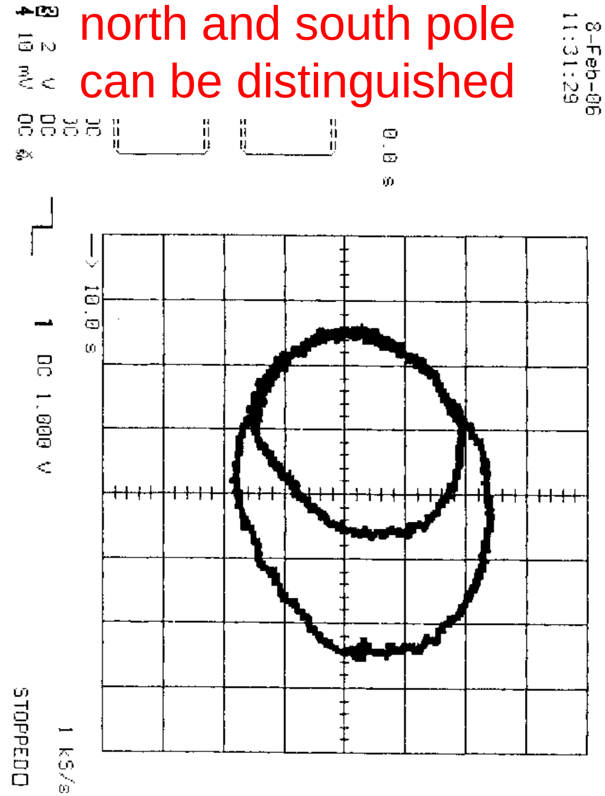


a) theoretisch



b) experimentell

north and south pole can be distinguished

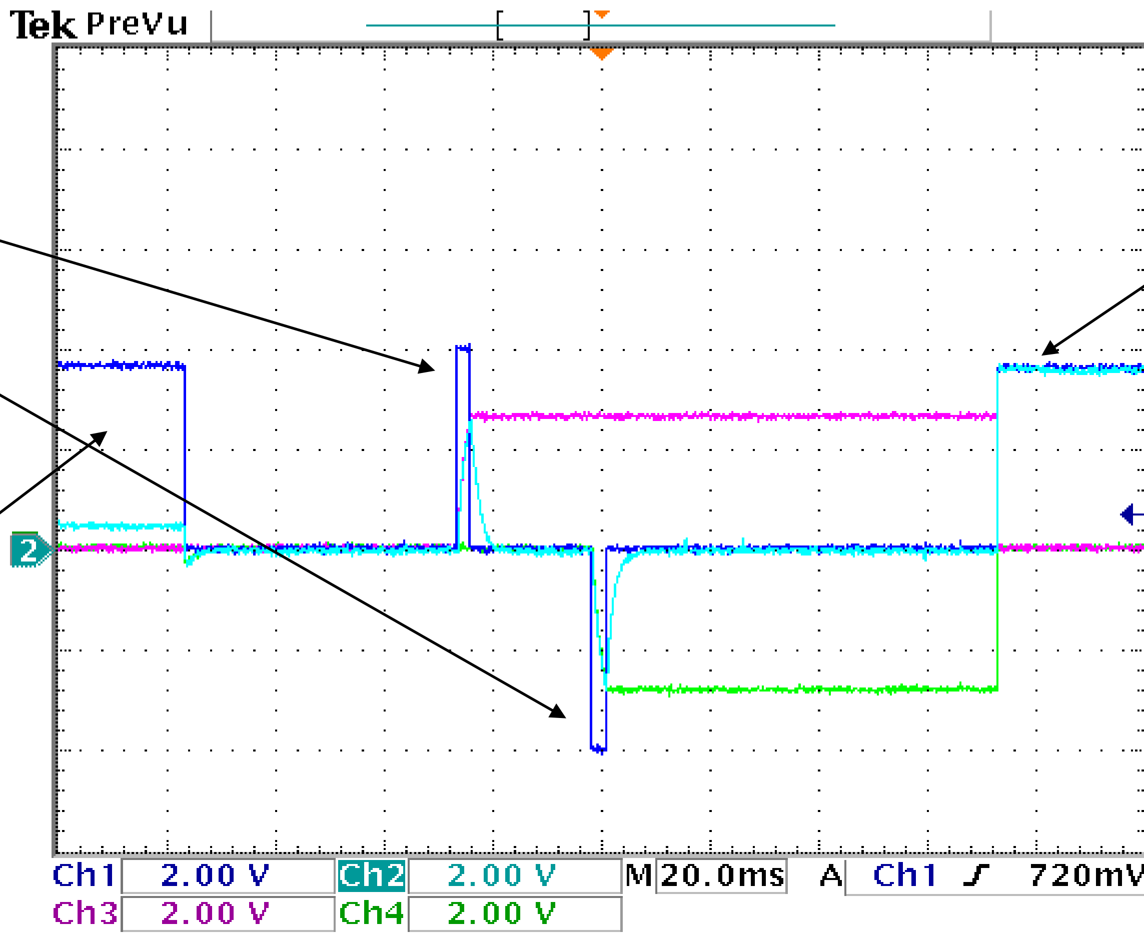


trajectory of stator admittance
(SMPMSM, carrier frequency $f_c = 0.5$ kHz)

Stator Admittance in Complex Plane

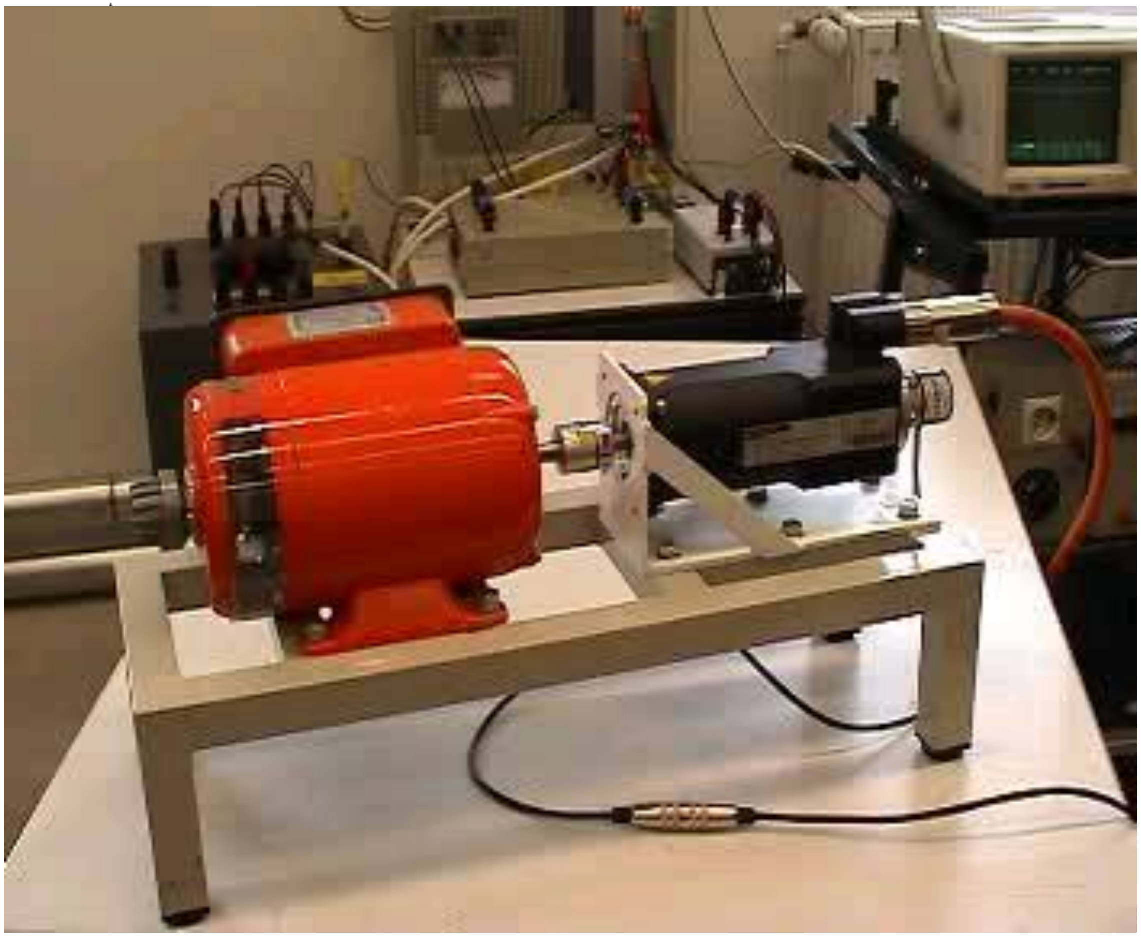
Injection of 2 Voltage Pulses in +d and -d

Pulses in
+d and –d
Evaluate current
response

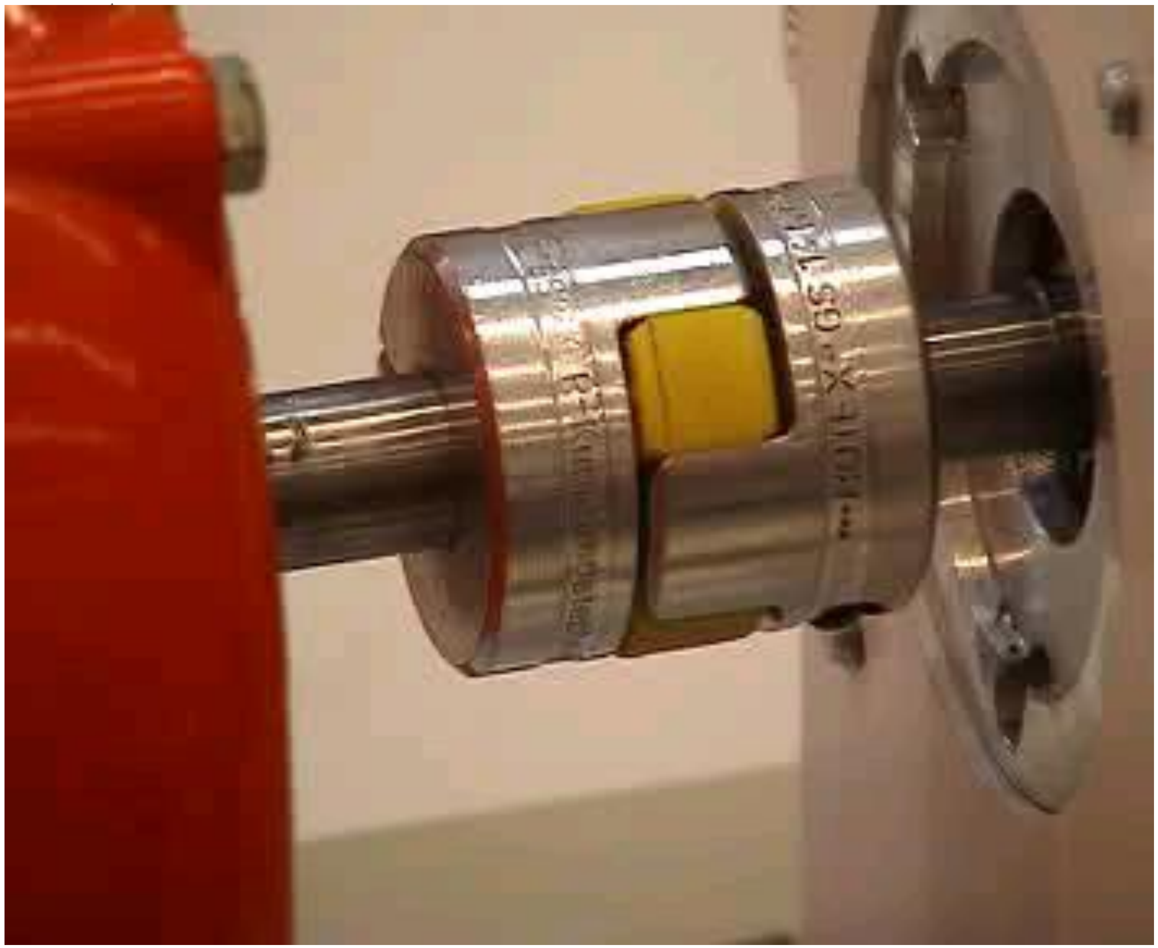


0° difference

180° difference



Drive with Speed Control



Step Response of Encoderless Position Control

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Stationary Signal Injection Methods

according to R. Lorenz, S.-K. Sul, R. Kennel, etc.

- when the basic idea is

  to use the electrical machine itself as a resolver …

… the performance of this type of encoderless control
must be more or less equal
to a control with a low performance resolver …

because the electrical machine is designed
to be an electrical machine

and not to be a good resolver !

Practical Experience with an Industrial Servo Drive

Implementation of a sensorless control into a servo drive of WEG

- training of a development engineer
  2 x 1 week in our laboratory
- programming of additional software
  in manufacturer‘s factory
- delivery of prototype
  after ca. 3 months
- presentation on Hanover Fair
  in April 2006

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meanwhile :
more industrial applications

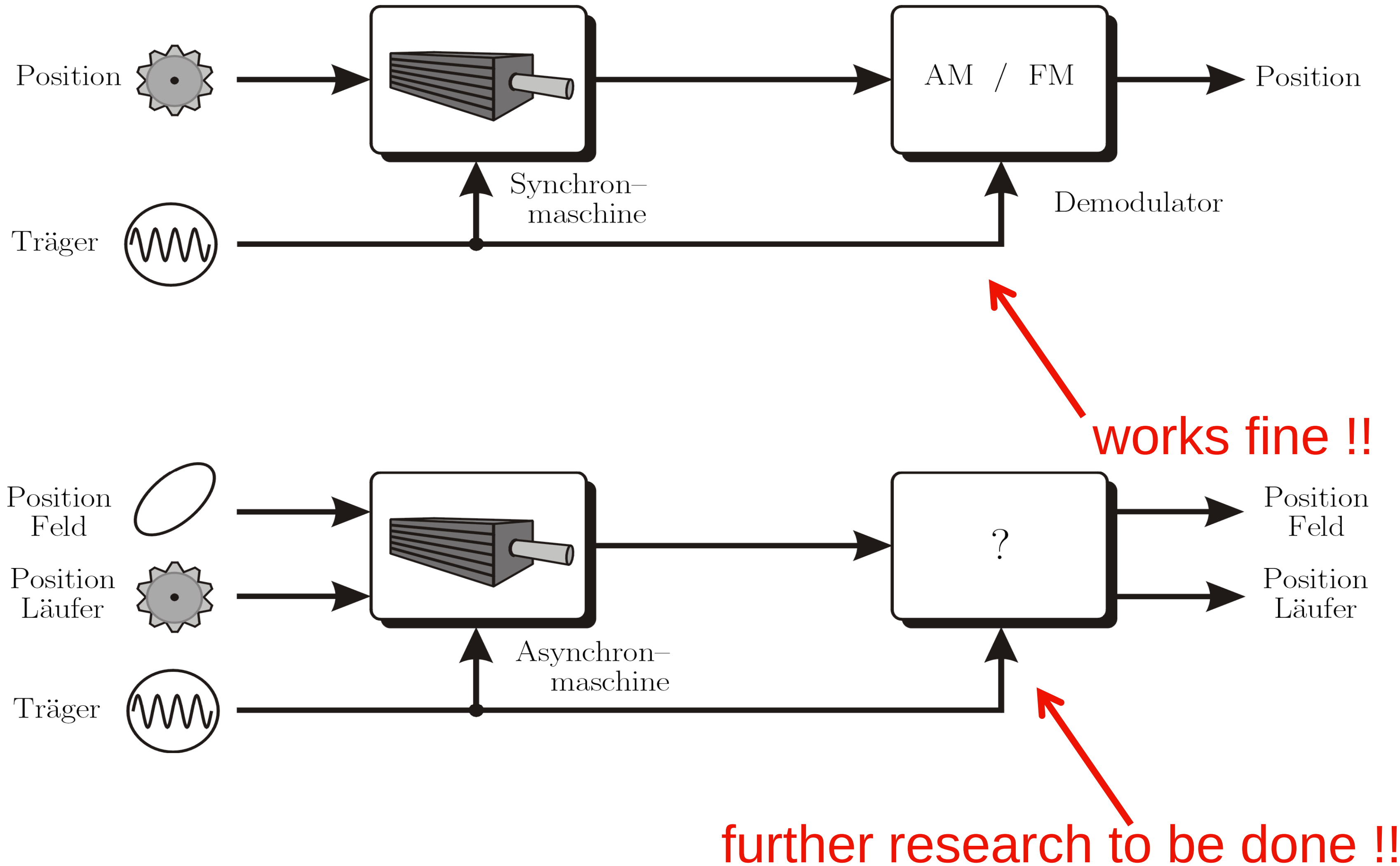
- WEG (Brazil) – as mentioned before
- BAUMÜLLER – same experiences as WEG
- TRÜTZSCHLER – successful application in textile machinery
- two more companies – who do not want to be mentioned
- ABM Greiffenberger – advertising actively on SPS/IPC/Drives 2010

the concept of encoderless control as presented here
works similar to radio broadcasting :

the information of rotor position
is modulated by a high frequency signal

the information is demodulated / extracted
from motor currents

modulation on a high frequency carrier by the motor itself



Further Research Activities

- are there demodulation schemes being able to distinguish
  the different current responses resulting from rotor and field anisotropies ?
- design of a parameter independant encoserless control
  for induction machines without voltage sensors

Saliency based Encoderless Predictive Torque Control without Signal Injection

P. Landsmann, D. Paulus, P. Stolze and R. Kennel
Technische Universitaet Muenchen
Munich Germany

Basic Idea:

A Predictive Torque Controller
neglecting the saliency in the model
causes a prediction error
which contains the angle information

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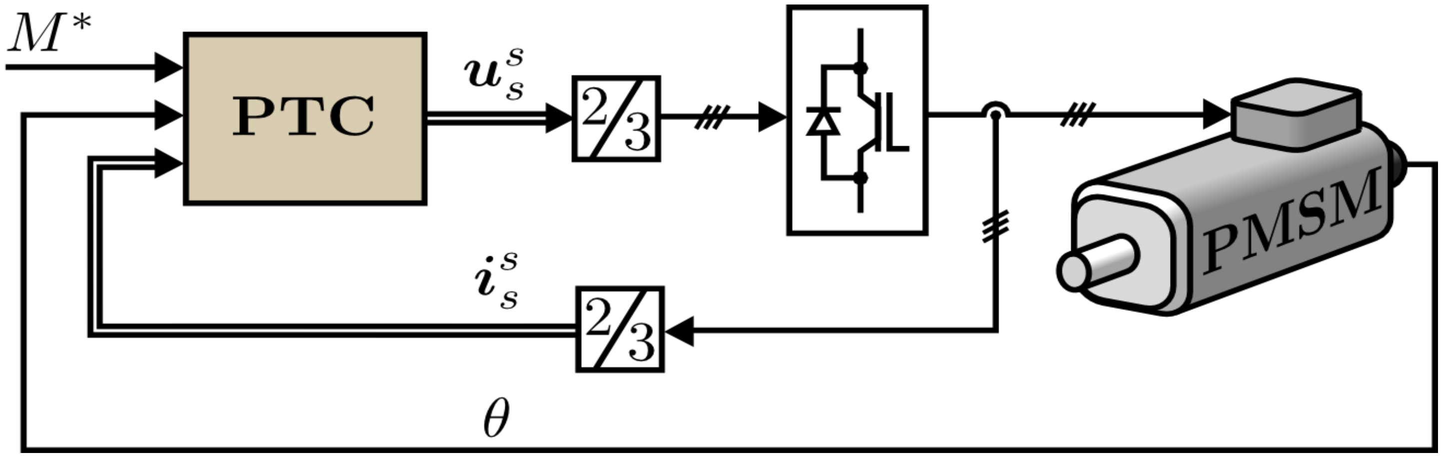
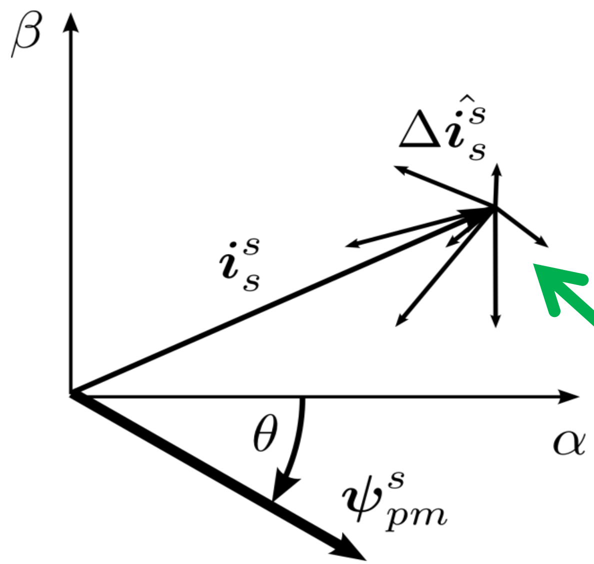
Arcisstr. 21, D-80333 Munich - peter.landsmann@tum.de

Predictive Torque Control



Predictive Torque Control



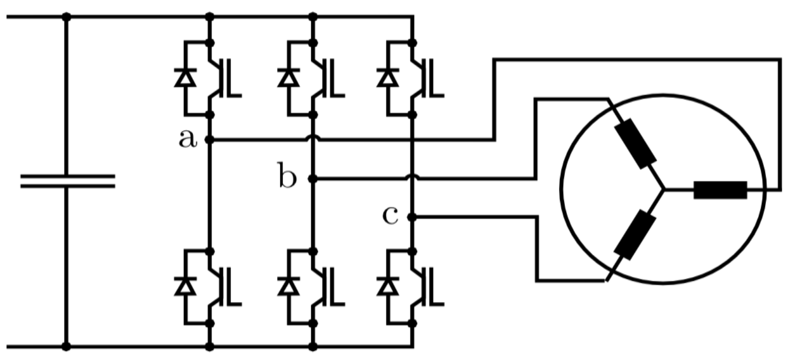
→ Current and PM flux linkage from measurements

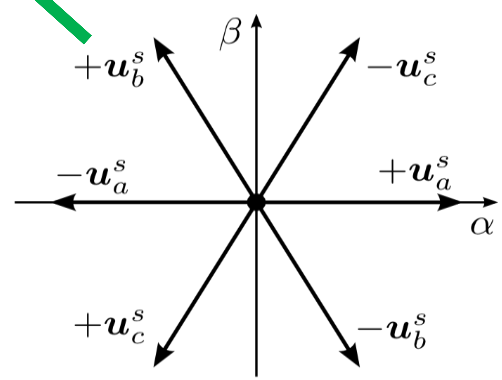
→ 7 voltages vectors from inverter

→ prediction of current and respective torque

$$M = {\boldsymbol{i}_s^s}^T \mathbf{J}\ \boldsymbol{\psi}_{pm}^s \qquad \mathbf{J} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

→ Selecting optimum of cost function





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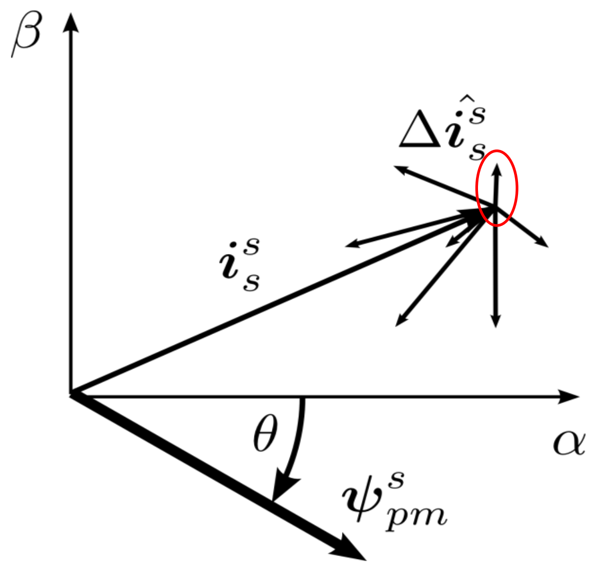
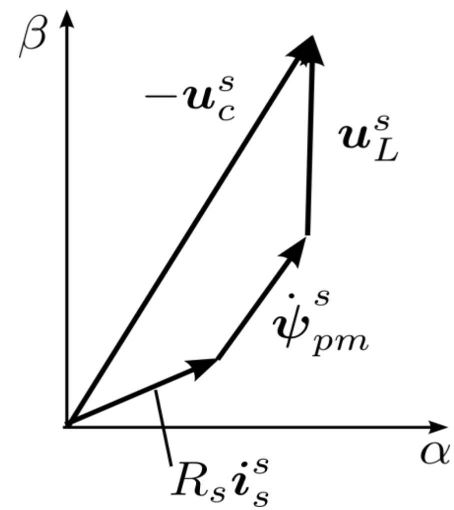
Predictive Torque Control





→ Discrete model of the machine

→ Current prediction based on ***mean*** inverse inductance

$$\boldsymbol{u}_L^s = \boldsymbol{u}_s^s - R_s\boldsymbol{i}_s^s - \mathbf{J}\omega\boldsymbol{\psi}_{pm}^s$$

$$\Delta\hat{\boldsymbol{i}}_s^s = Y_\Sigma \boldsymbol{u}_L^s \Delta t$$

$$Y_\Sigma = \frac{1}{2}\left(\frac{1}{L_d} + \frac{1}{L_q}\right)$$

Saliency Tracking Approach

Predicted current progression

$$\Delta\hat{\boldsymbol{i}}_s^s = Y_\Sigma \boldsymbol{u}_L^s \Delta t$$

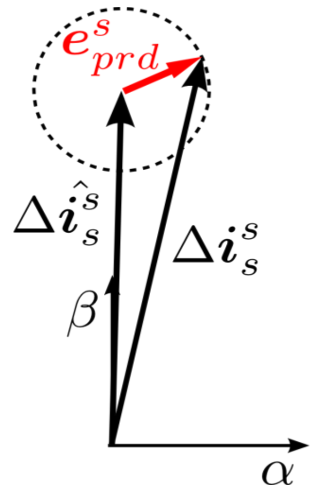
$$Y_\Sigma = \frac{1}{2}\left(\frac{1}{L_d} + \frac{1}{L_q}\right)$$

Real current progression

$$\Delta\boldsymbol{i}_s^s = \mathbf{L}_s^{s\,-1}\boldsymbol{u}_L^s\Delta t$$
$$= Y_\Sigma \boldsymbol{u}_L^s \Delta t + Y_\Delta \mathbf{S}(\theta)\boldsymbol{u}_L^s \Delta t$$

$$Y_\Delta = \frac{1}{2}\left(\frac{1}{L_d} - \frac{1}{L_q}\right)$$

$$\mathbf{S}(\theta) = \begin{bmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{bmatrix}$$



Prediction error

$$\boldsymbol{e}_{prd}^s = \boldsymbol{i}_s^s - \hat{\boldsymbol{i}}_s^s$$
$$= \Delta\boldsymbol{i}_s^s - \Delta\hat{\boldsymbol{i}}_s^s$$
$$= Y_\Delta \mathbf{S}(\theta)\boldsymbol{u}_L^s$$

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Saliency Tracking Approach

Measured prediction error

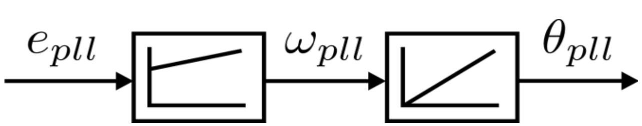
$$\boldsymbol{e}^s_{prd} = \boldsymbol{i}^s_s - \hat{\boldsymbol{i}}^s_s$$

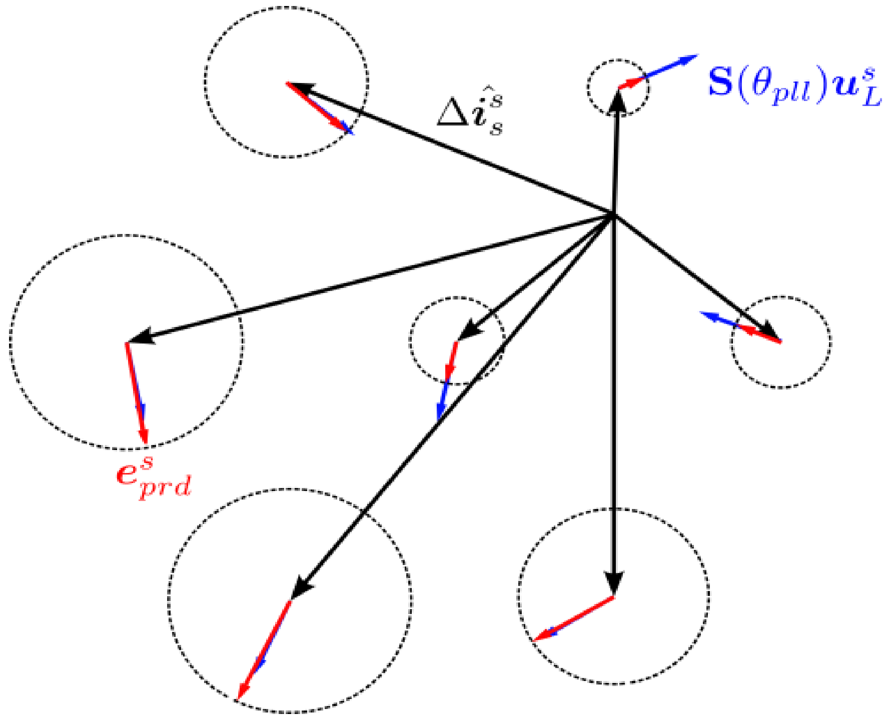
Reconstructed prediction error

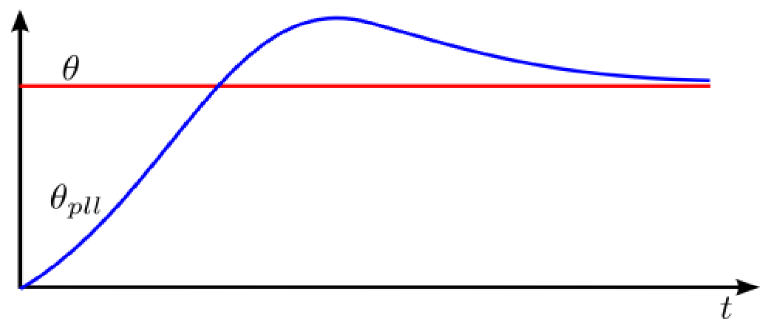
$$\boldsymbol{e}^s_{prd} = \mathbf{S}(\theta_{pll})\boldsymbol{u}^s_L$$

PLL controller input

$$e_{pll} = \left(\boldsymbol{i}^s_s - \hat{\boldsymbol{i}}^s_s\right) \mathbf{J}\ \mathbf{S}(\theta_{pll})\boldsymbol{u}^s_L$$





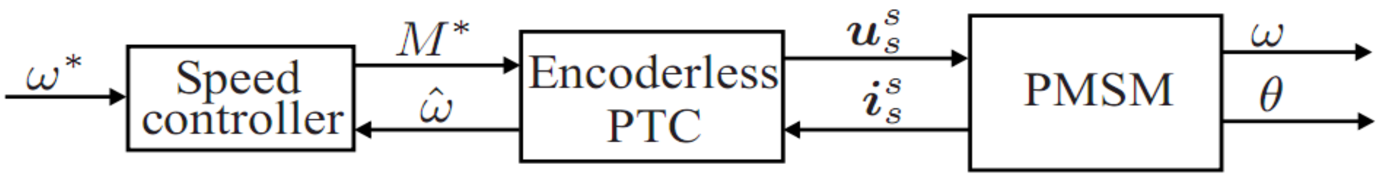


Simulation Results for PMSM

Simulation parameter of PMSM

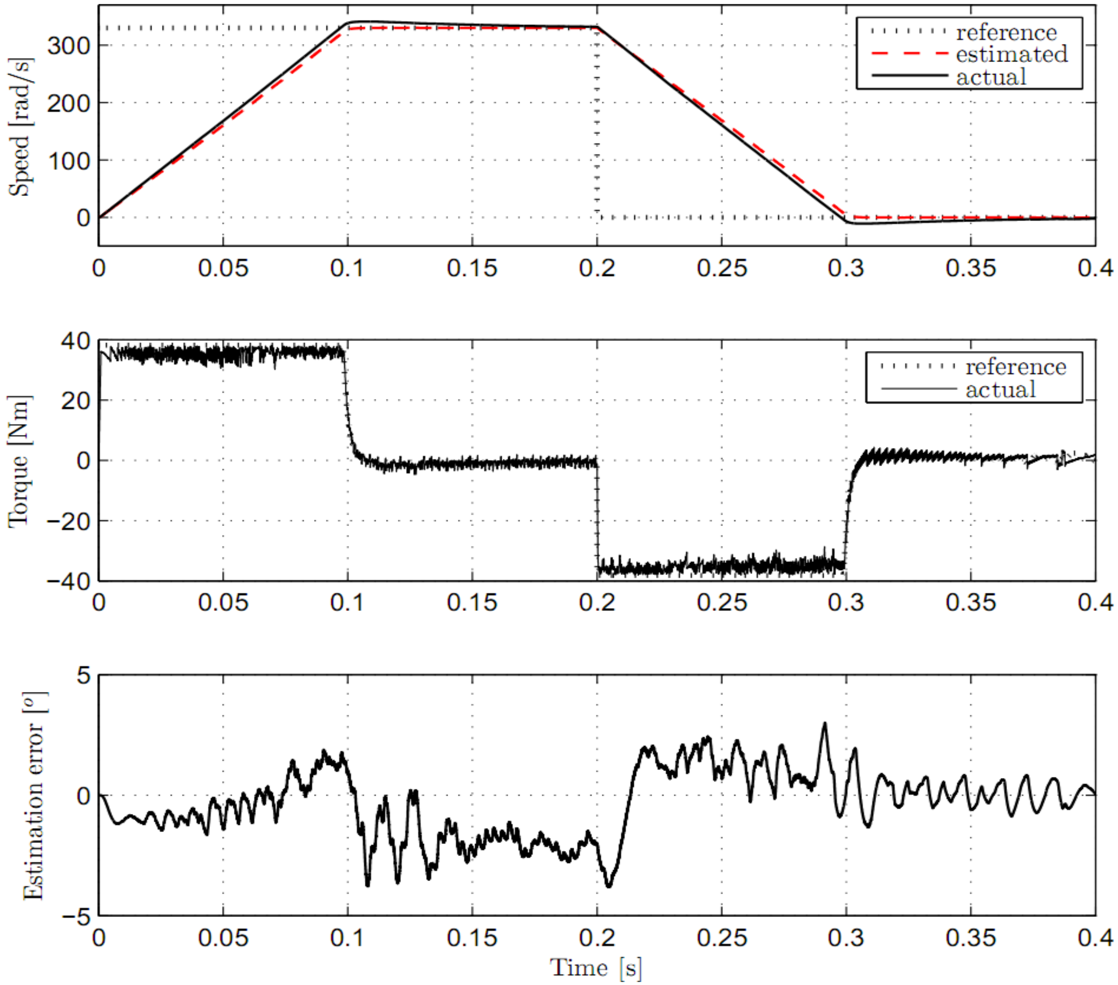
Stator resistance	R_s	10.0	$m\Omega$
d-axis inductance	L_d	13.5	mH
q-axis inductance	L_q	15.0	mH
saliency ratio	L_d/L_q	90.0	$\%$
current limitation	i_{max}	30.0	A

Speed controlled encoderless predictive torque control



Simulation Results for PMSM

Speed controlled step response to rated speed



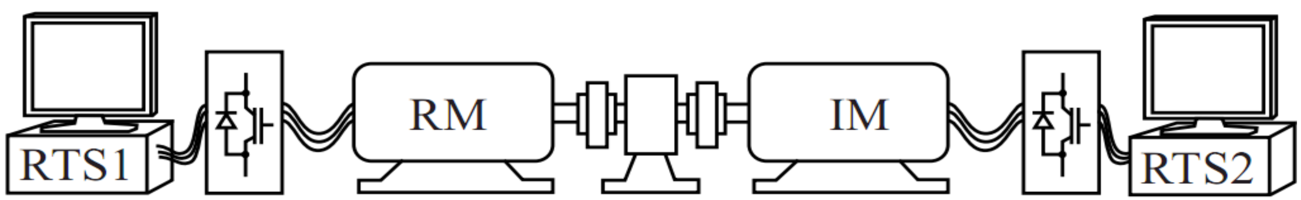
→ very good dynamics in simulation

→ dependency on torque gradients

Measurements with Reluctance Machine

Data of transverse laminated RM

Pole pairs	2	
Nominal power	1.1	kW
Rated current	3.5	A
Rated mechanical torque	7	Nm
Rated electrical speed	314	rad/s



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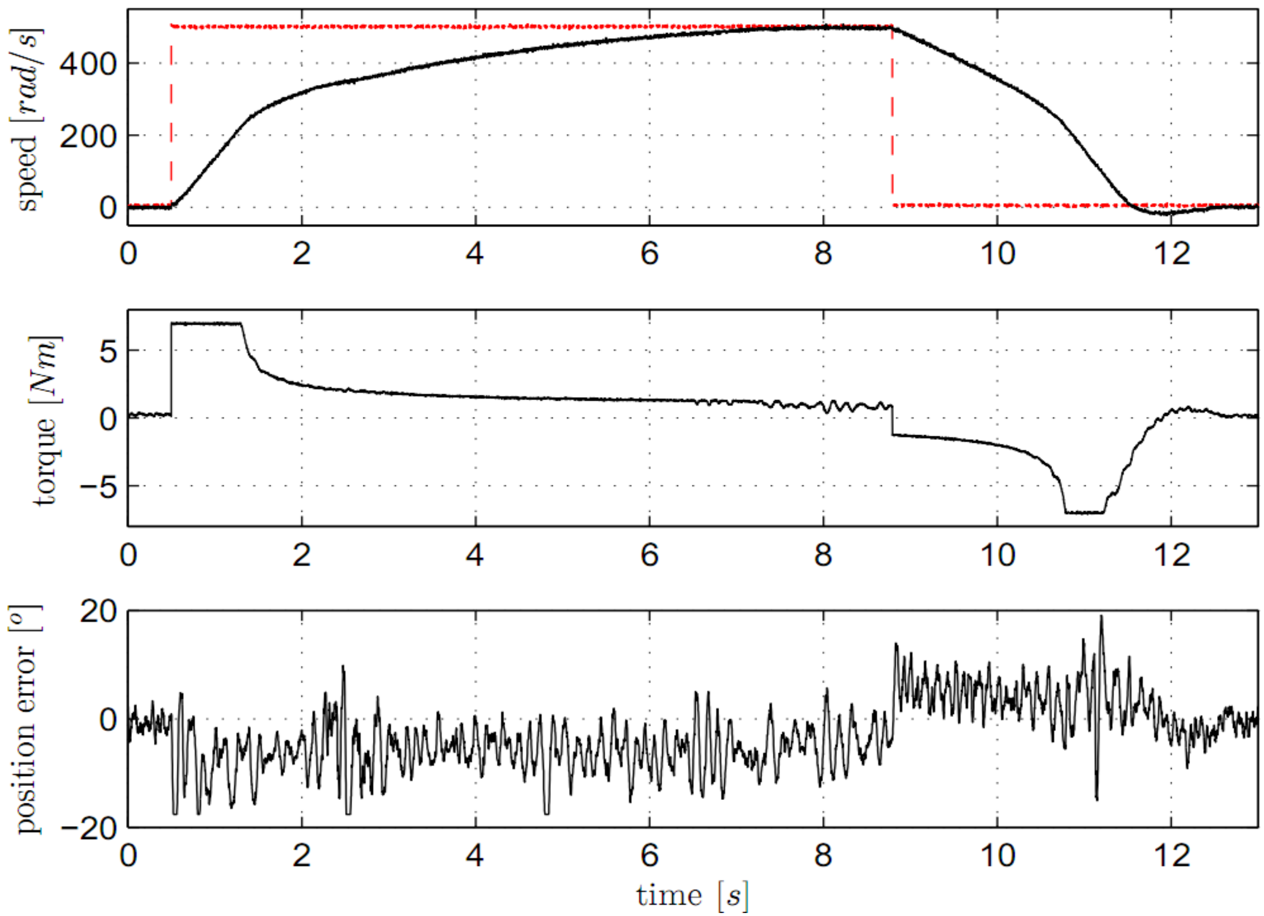
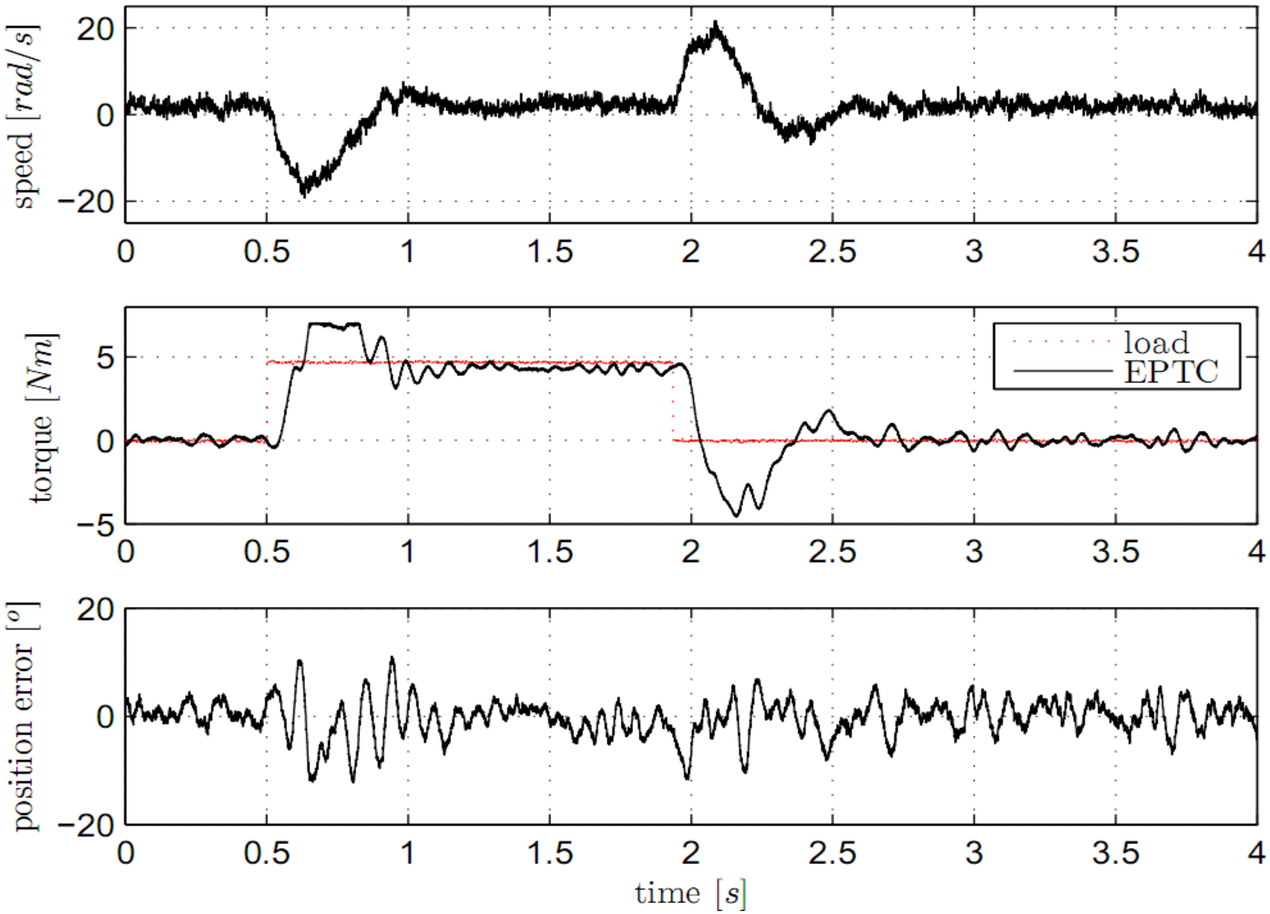
Measurements with Reluctance Machine

Speed controlled step response to 160% rated speed



Measurements with Reluctance Machine

Response to 66% rated torque load step at speed controlled standstill



Summary

Proposed Scheme:

- Neglect the saliency in PTC equations
- Prediction error contains angle information
- Reconstruct Prediction Error using PLL angle
- Vectorproduct of both is PLL input

Benefits:

- Saliency based:
  ➩ permanent operation at standstill
- No signal injection:
  ➩ operation at high speed as well as at standstill

Encoderless Control with Arbitrary Injection

„Limitations“ of HF Injection Methods

- HF injection → voltage margin → limitation to medium and low speed

- Restriction to rotating or alternating shape due to algorithmic reasons

Meaning of „Arbitrary“

- No physical necessity for injection shape

- Basically **any** current ripple contains the saliency angle information

- Finding a way to exploit this provides additional degrees of freedom

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Encoderless Control with Arbitrary Injection

„Limitations“ of HF Injection Methods

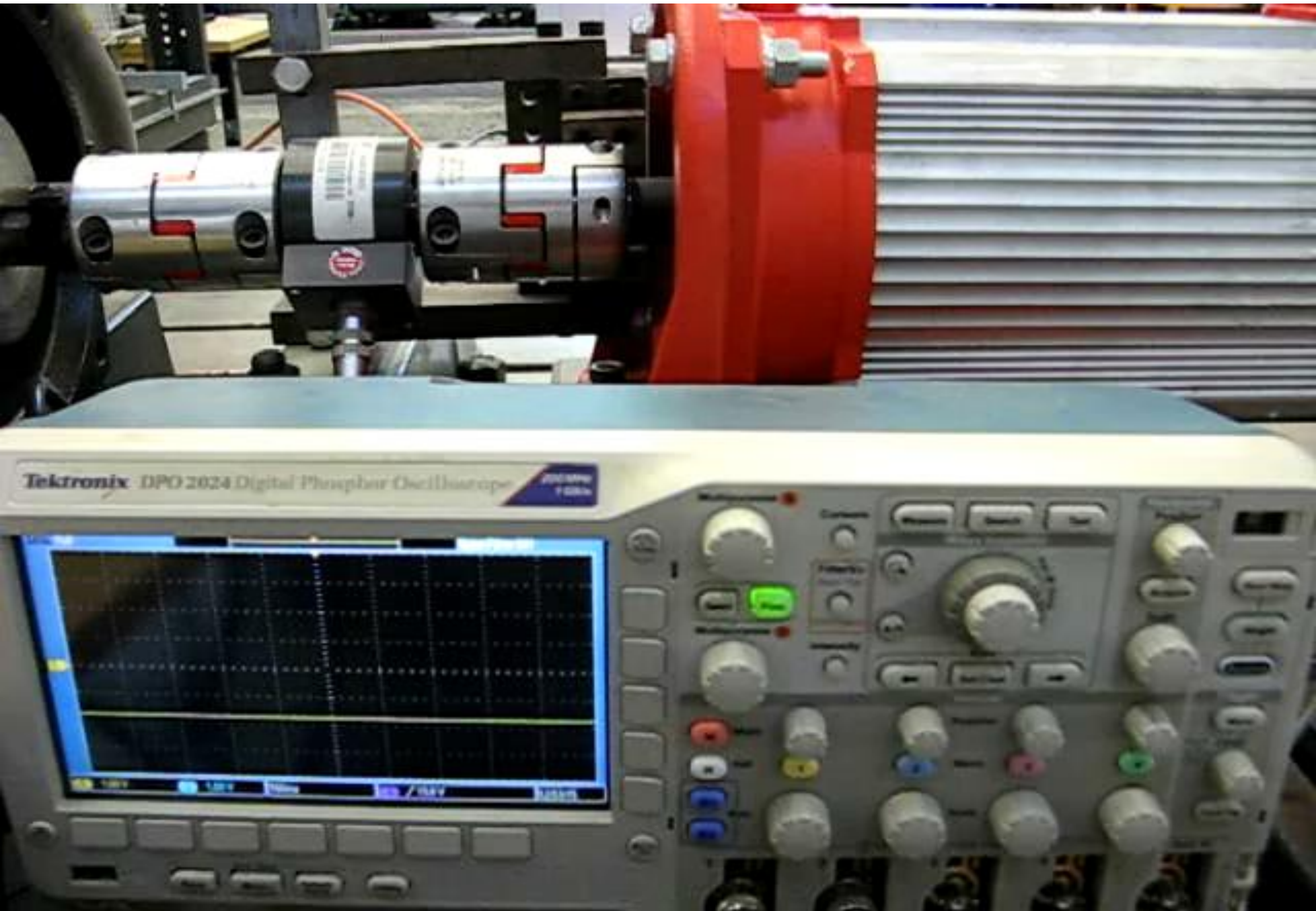
… usually the current ripple caused by the inverter switchings
are sufficient to exploit the rorot position …

Meaning of „Arbitrary“

- No physical necessity for injection shape

- Basically **any** current ripple contains the saliency angle information

… if not … any current ripple can eben be music !!!


Tektronix DPO 2024 Digital Phosphor Oscilloscope

Industrial Needs

- The proposed PTC (Predictive Torque Control) method
  works from standstill to maximum speed

  ☑ single scheme for wide speed range (no phase over)

- The sensorless control scheme presented here
  does not need additional voltage measurement devices
  - neither on the machine/motor side nor on the line side

  ☑ no additional noise (except usual noise by inverter supply)

- As long as there is a detectable saliency
  PTC is very robust to variations of the motor parameters

  ⇢? insensitivity with respect to parameter variations

further research to be done !!

Signal Injection Method

according to J. Holtz, H.Pan, etc.

- this is basically a current injection method
  → voltage sensors are necessary !!!
- it is possible to use current derivatives
  instead of motor voltages

→ measuring current derivatives, however,
by standard current transducers is not really possible

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Basic Principle
of Transient Current Response Detection

- just use the voltage pulses provided by the PWM anyway
- detect the anisotropy dependant (transient) current responses

Practical Problems

- sometimes the original PWM patterns are too short
  ↳PWM patterns have to be modified (→ several schemes !)
- current derivation is needed to detect inductance variations

Position Estimation by Pulse Injection

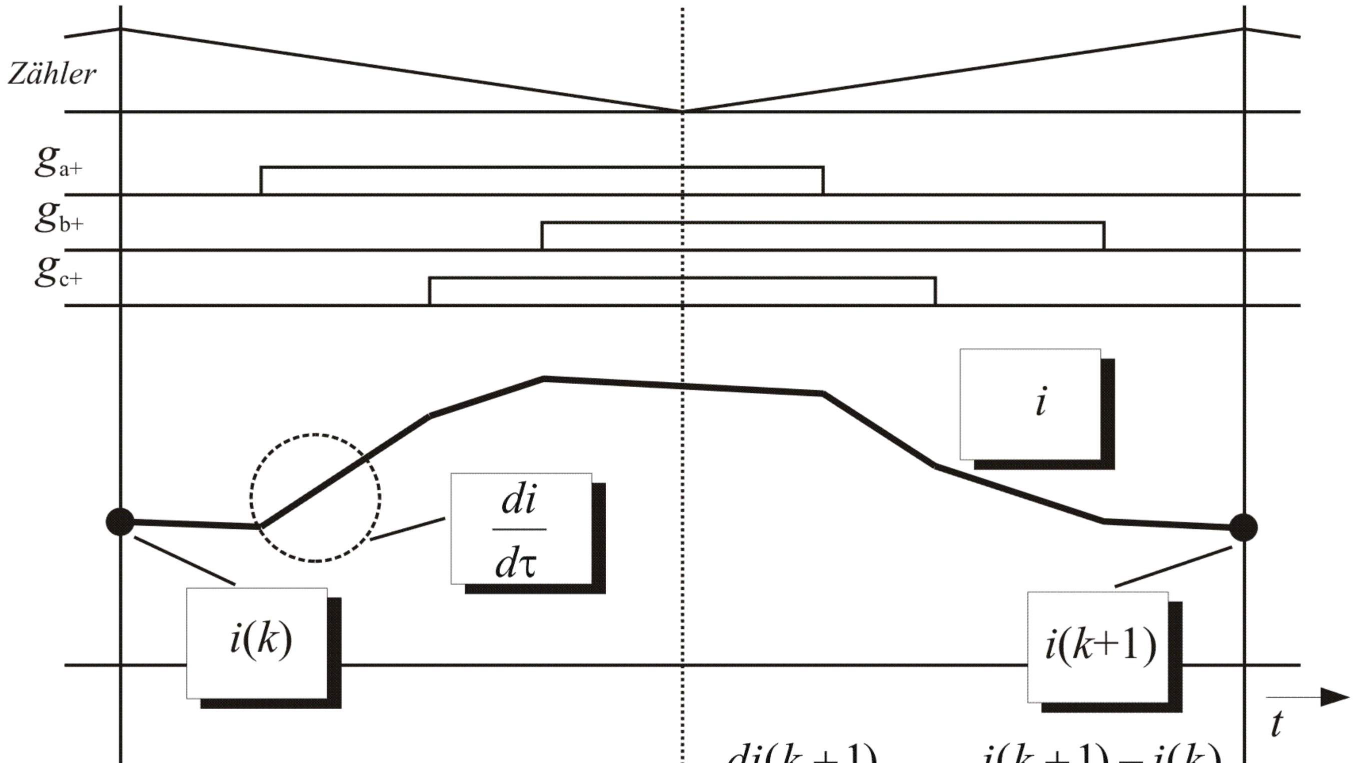
- the stator leakage inductance variations can be detected in the motor voltages or in the current derivations

$$\frac{di_a(u_1)}{dt} = K\left(2 - \frac{l_\Delta}{l_{\sigma 0}}\cos(n\theta)\right)$$

$$\frac{di_b(u_1)}{dt} = K\left(1 + \frac{l_\Delta}{l_{\sigma 0}}\cos\left(n\left(\theta - \frac{4\pi}{3}\right)\right)\right)$$

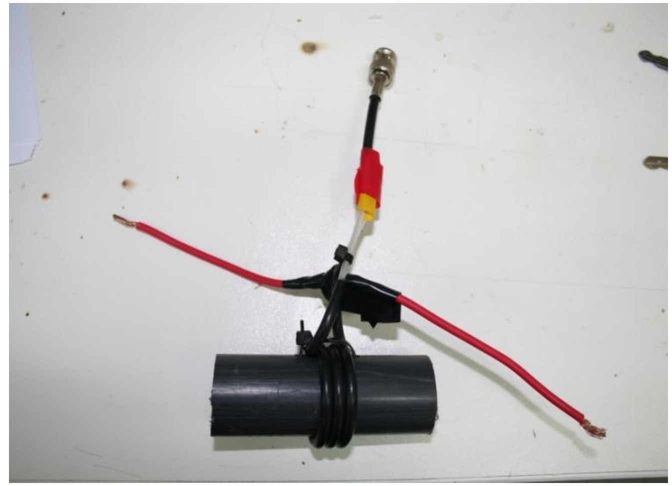
$$\frac{di_c(u_1)}{dt} = K\left(1 + \frac{l_\Delta}{l_{\sigma 0}}\cos\left(n\left(\theta - \frac{2\pi}{3}\right)\right)\right)$$

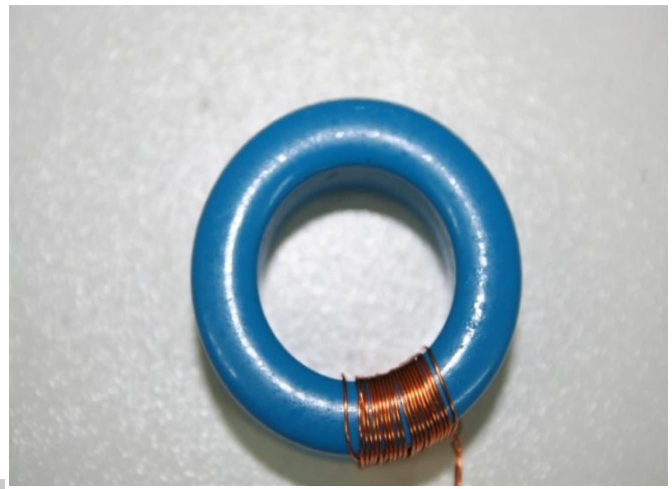
☑ **the availability of the current derivations would be very helpful**



$$\frac{di(k+1)_{\text{disk}}}{d\tau} \cong \frac{i(k+1)-i(k)}{\Delta\tau}$$

Current Derivative Sensors as used at the University of Malta





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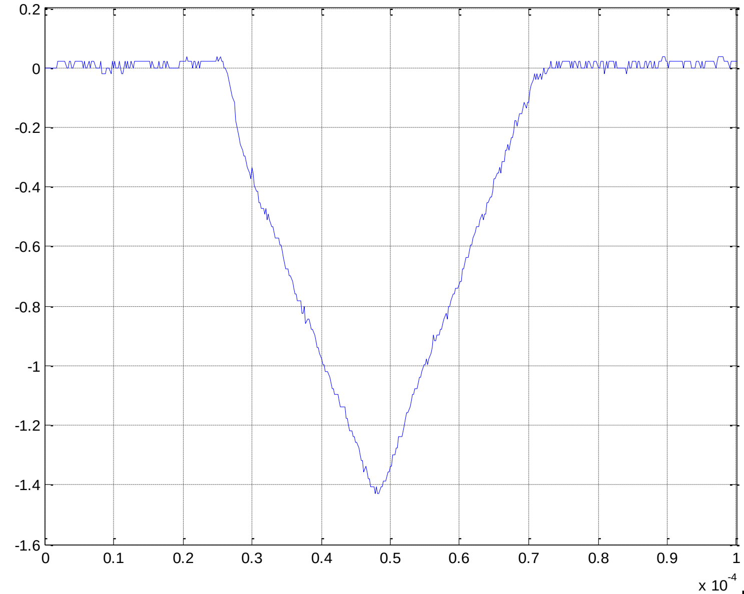
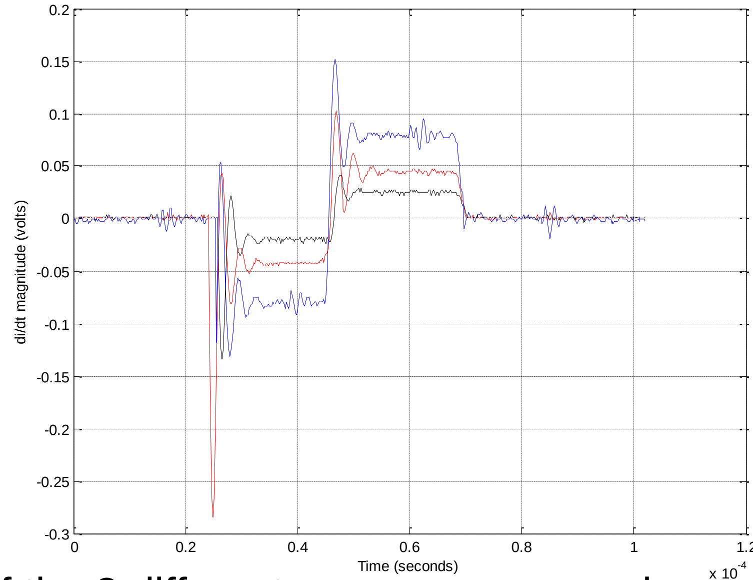
Coax Sensor Responses
as measured at the University of Malta



ramp from 0 - 1.4 A is applied in 20 µs



Response of the 3 different coax sensors used.
Blue trace shows results using at 5:20 turn sensor,
Red shows a 5:5 turn sensor and
black shows results for a 3:3 turn sensor,
the settling time for three cases is approximately equivalent displaying a deviation from a mean of 10µs of +/-5%

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Coaxial Coils as used at Wuppertal University

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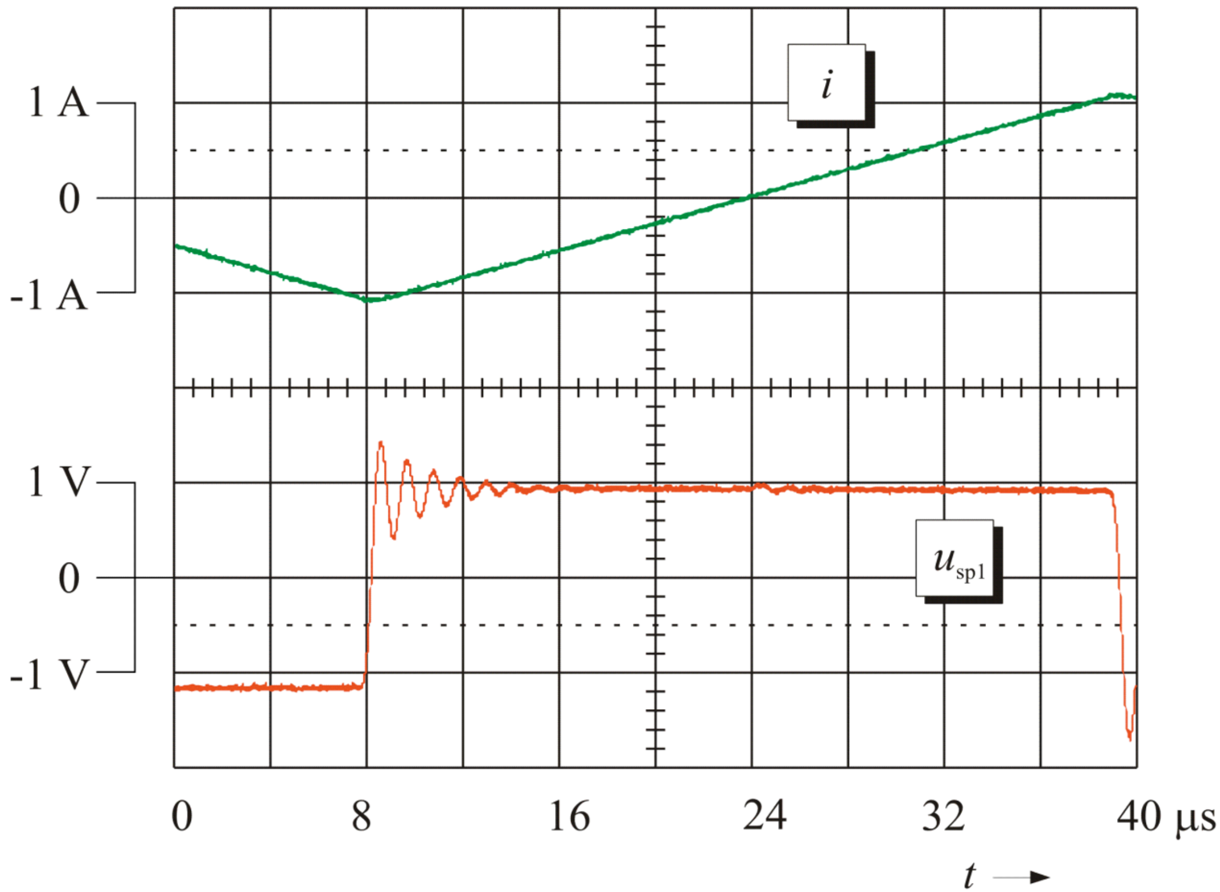
Derivative Output Signal of Coaxial Coil



further investigations

- will industry accept (additional) current derivation sensors (e. g. Rogowski type) ?

☑ **probably not (nearly the same problem as with additional voltage sensors)**

- can the "standard" current sensors be used for derivation measurement ?

☑ **Measuring sequentially 2 currents and calculating the difference is possible**

problem 1 : measuring time cannot be synchronized with PWM

problem 2 : small differences need high resolution A/D conversion

❈ **can "standard" current sensors provide an additional derivation output ???**

(e. g. based on the compensation voltage available inside)

Compensation Current Sensor

- … compensate the magnetic field of the primary current
  by a second magnetic field produced by a secondary coil
- the respective compensation controller/regulator
  is feeding the secondary coil by a voltage

$$u = L \; di/dt$$

- → a current derivative signal
  does already exist inside the current sensor
- however, is the signal quality sufficient
  for sensorless/encoderless control of induction machines ???

can this be made available for customers ???

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Compensation Current Sensor

- contact meetings with current sensor manufacturers have already taken place
- current sensor manufacturers hesitate to provide the internal signal for external use, because the basic internal signal has bad accuracy

  they fear a hint for their business by any bad accuracy of any signal in the data sheet
- sensorless/encoderless control, however, does not require good accuracy of the current deviation signal, it requires good linearity only

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some more experiences in encoderless control

- Bolognani reported (in 2006 ?) … but that was discussed by Alan Jack before !!

- … saturation in „q“ direction increases under load

(armature reaction)

- → difference between l_{cq} and l_{cd} decreases
- … and vanishes at a certain load

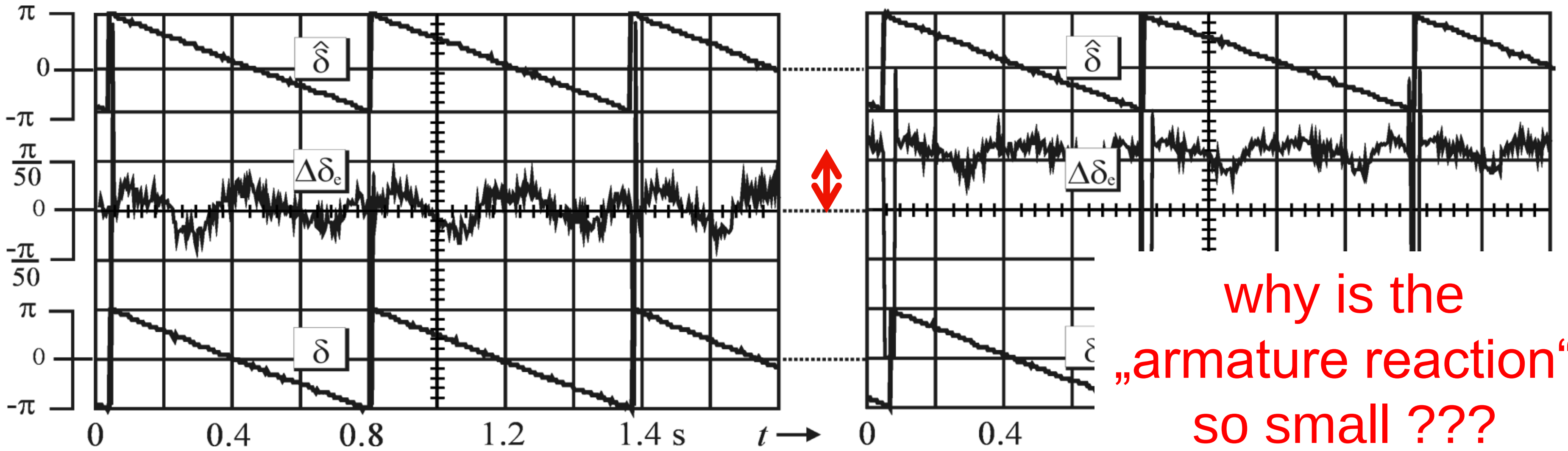
→ an encoderless tracking of the anisotropy

does not work any more

this effect appears

- around 2 to 3 times rated load with IPM motors
- around 5 to 6 times rated load with SMPM motors

Accuracy of the Rotor Position Identification under Load Conditions

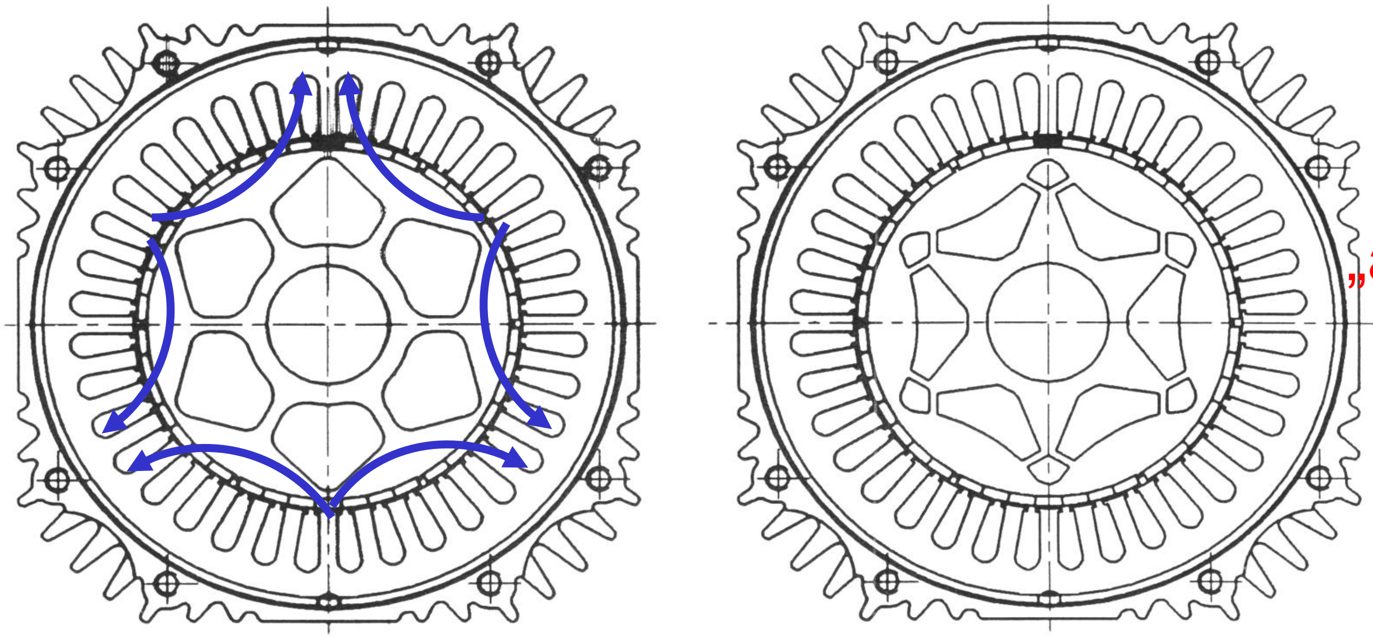


a) without load   b) rated load

(carrier frequency $f_c = 2$ kHz)

Accuracy of the Rotor Position Identification under Load Conditions

... because the usual rotor designs of servo motors (mechanical holes for inertia reduction)
do not allow a load depending displacement of the main field

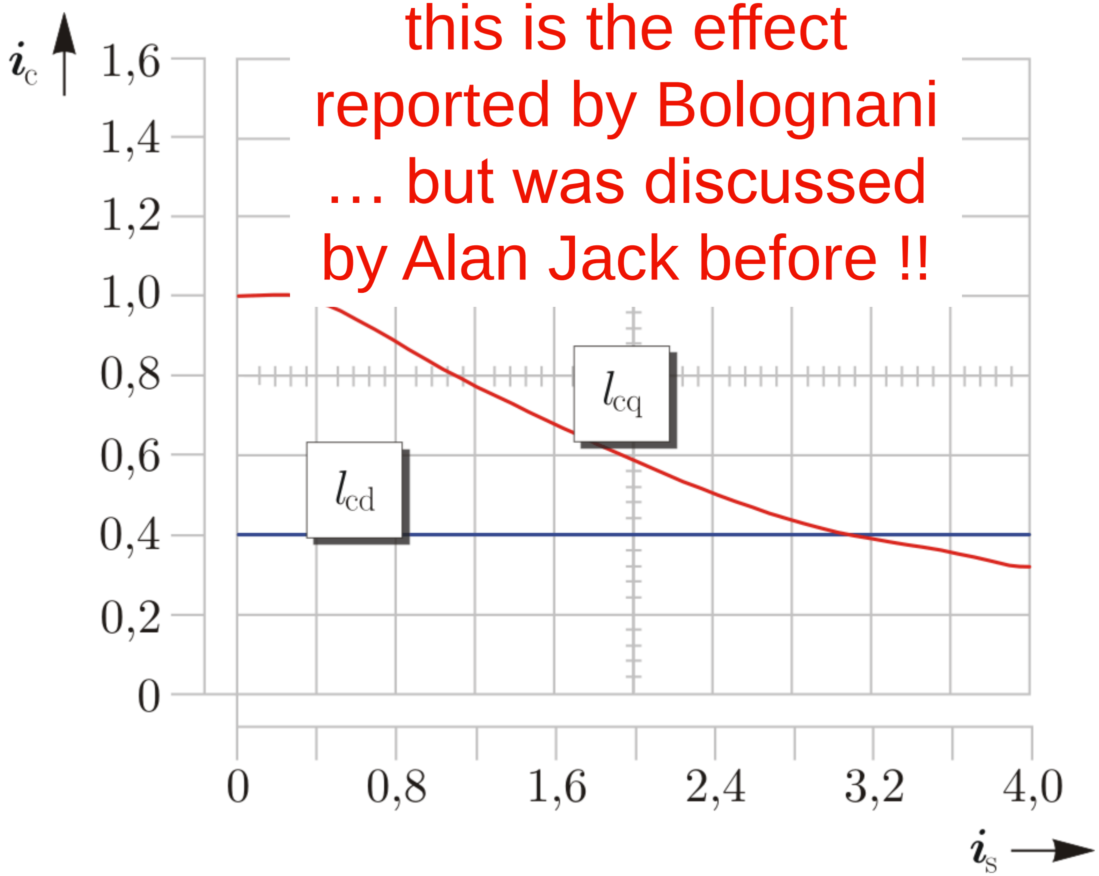


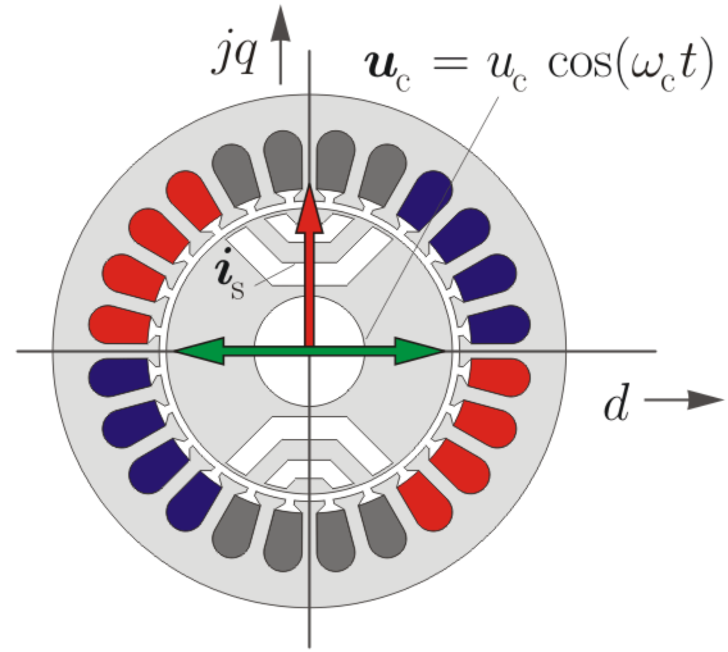
why is the „armature reaction“ so small ???

Load Dependancy of Saturation Anisotropy

(Armature Reaction)

this is the effect reported by Bolognani … but was discussed by Alan Jack before !!

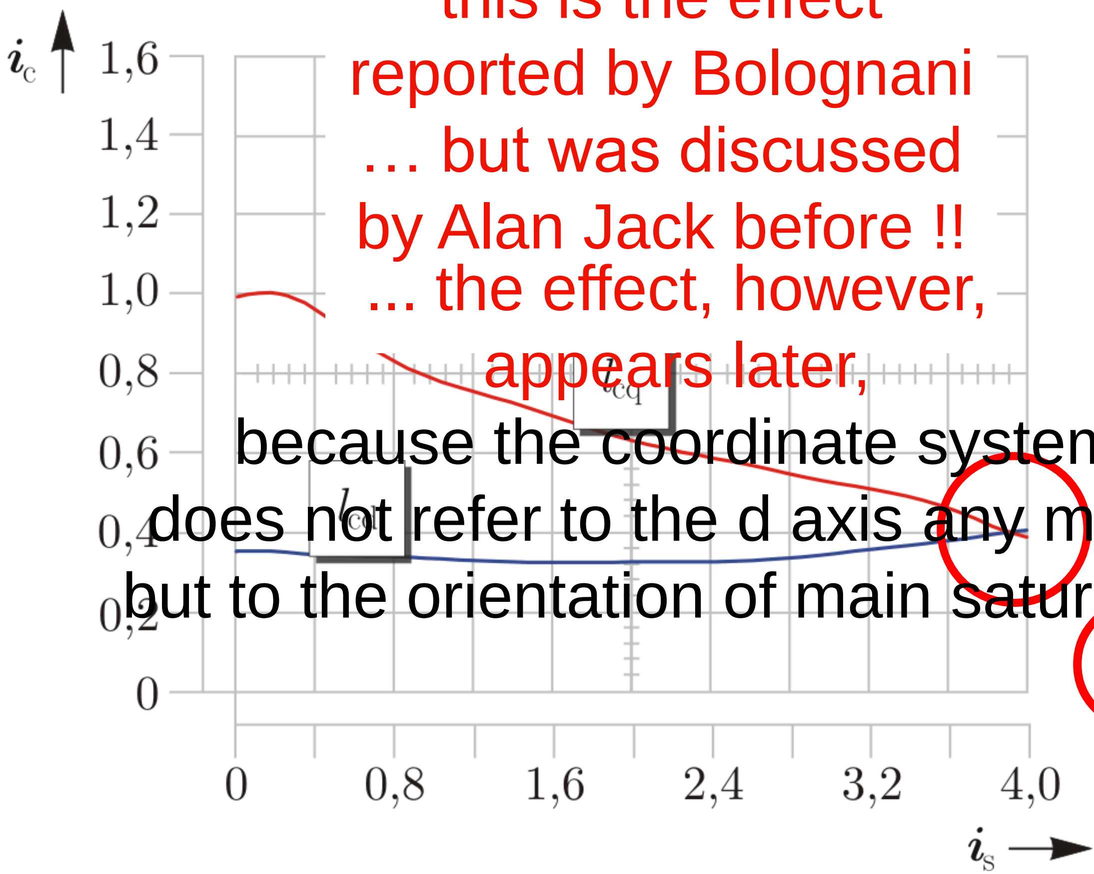


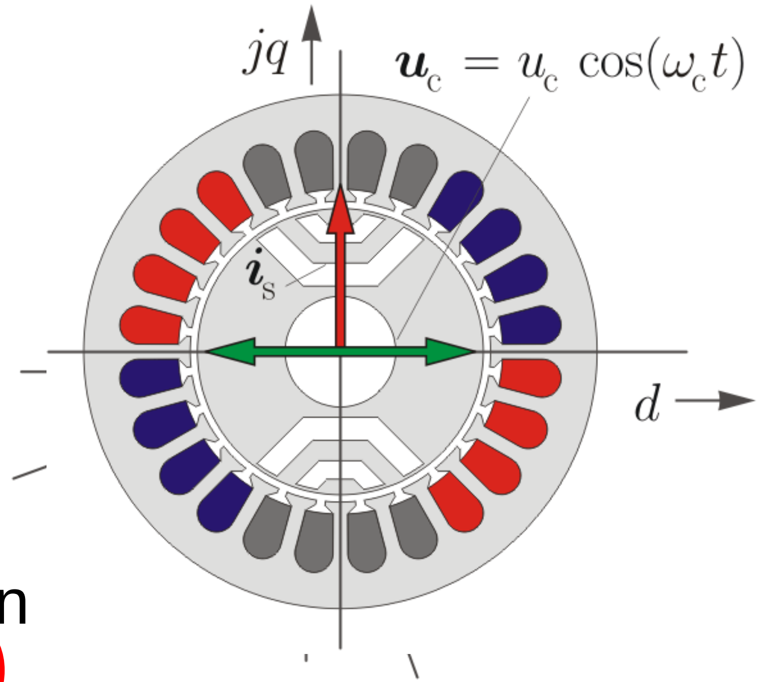


cross section of a
synchronous reluctance machine

Anisotropy
of a Non-Compensated Machine

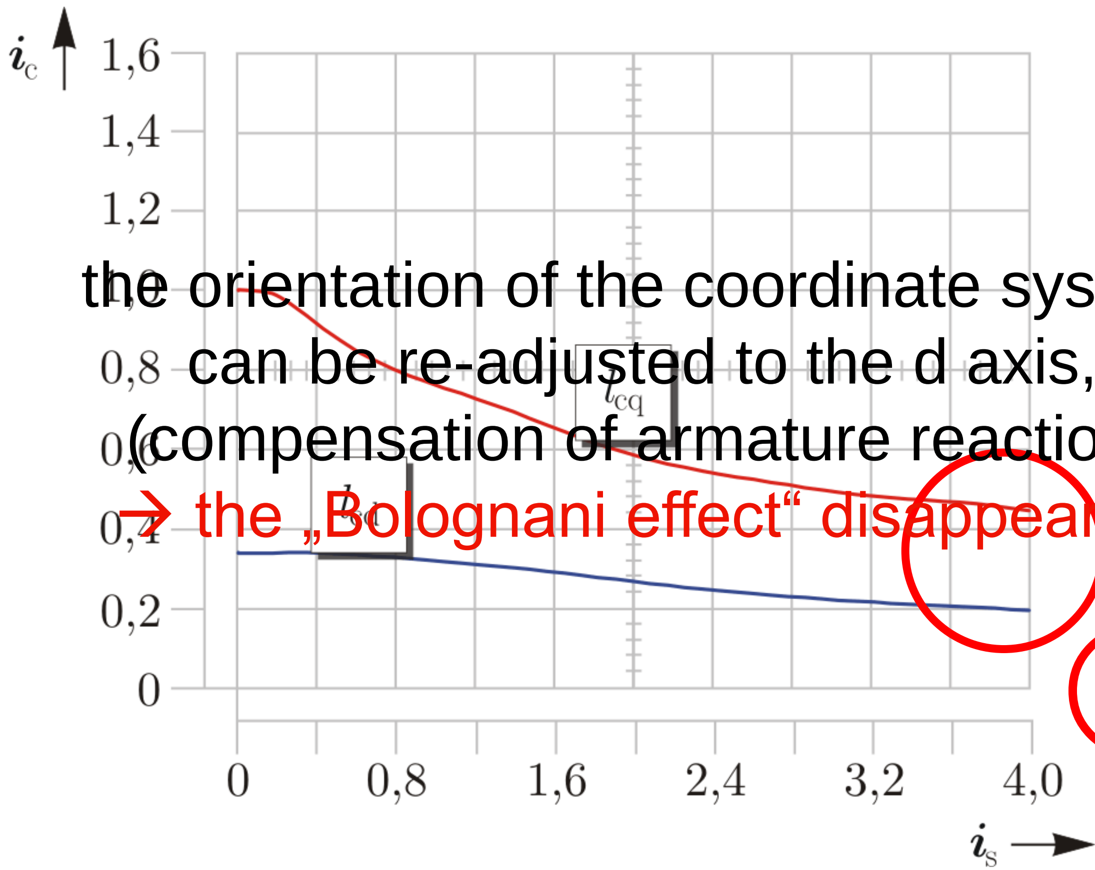
this is the effect
reported by Bolognani
… but was discussed
by Alan Jack before !!
... the effect, however,
appears later,
because the coordinate system
does not refer to the d axis any more,
but to the orientation of main saturation



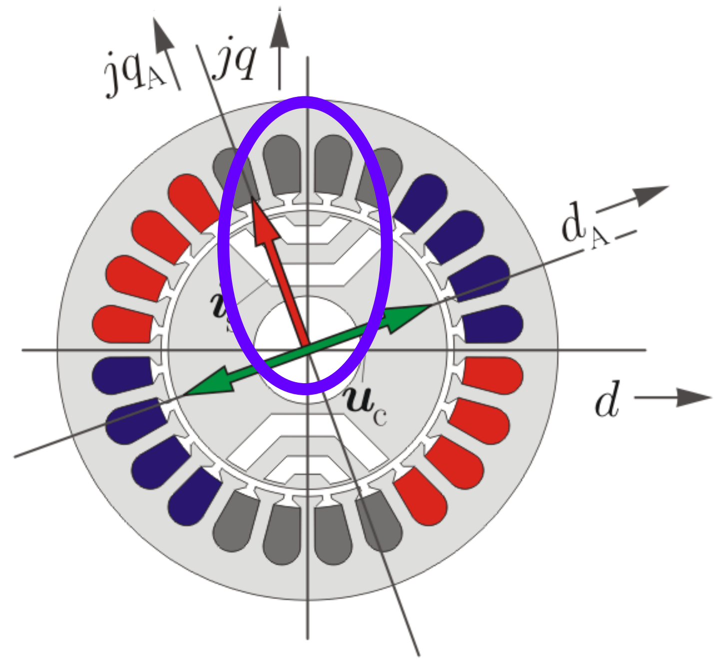


cross section of a
synchronous reluctance machine

Anisotropy
of a Compensated Machine



the orientation of the coordinate system
can be re-adjusted to the d axis,
(compensation of armature reaction)
→ the „Bolognani effect“ disappears !!



cross section of a
synchronous reluctance machine

meanwhile :
in certain applications difficulties occur

- there are motor designs,
  with difficulties in encoderless control
  under specific operation conditions

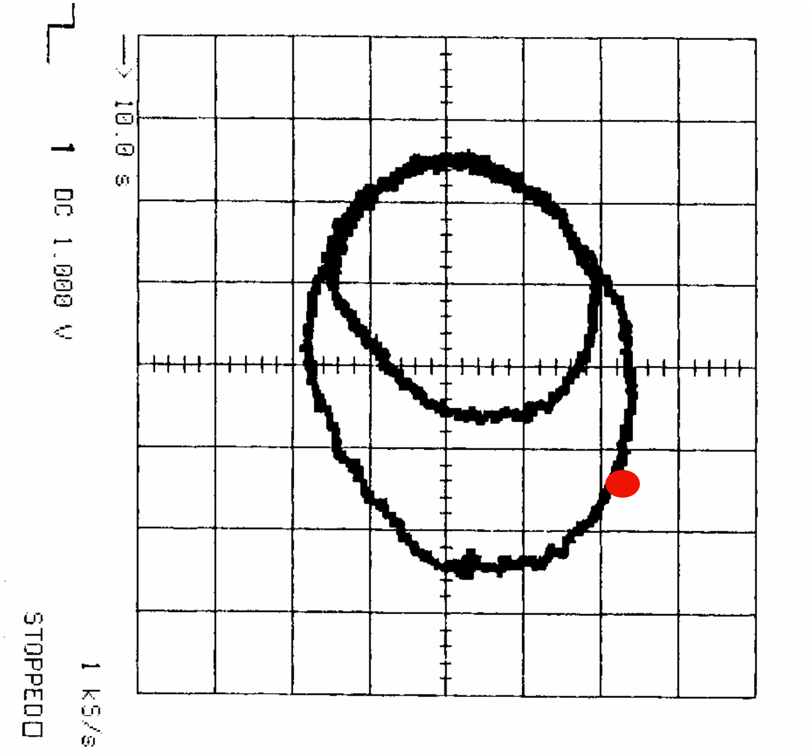
- there are motor designs,
  which cannot be controlled encoderless(ly)
  by an anisotropy tracking (PLL) controller at all

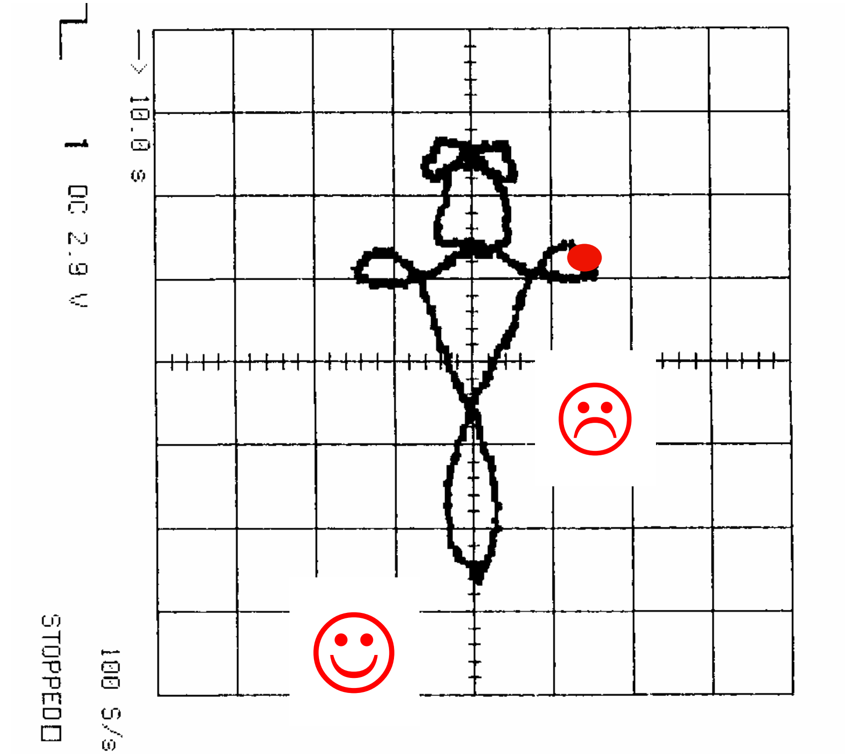
single tooth (bobbin) windings

cost reduction with respect to significant smaller end windings
→ will replace distributed windings in synchronous machines

disadvantage : magnetic field has non-sinusoidal distribution
→ several maxima / zero crossings per period possible

consequence : the tracking controller
does not catch the „position“ any more





consequence : the tracking controller
does not catch the „position“ any more
because it cannot find a maximum or minimum
q component of the high frequency current response

Further Research Activities

- enabling encoderless control to work with more sophisticated motor designs

  ☑ how can the schemes be improved ?

- encoderless control suffers under small detection signals (currents)

  ☑ can wavelet-based concepts improve anything ?

further research to be done !!

- which motor designs support encoderless control,

  ☑ high frequency models for electrical machines are needed

  – most well-known models consider the fundamental behaviour only

Actual EAL Activities

- encoderless control of more types of permanent magnet synchronous machines was successfully implemented in several industrial servo drives

☑ we can proceed with more collaboration partners and/or applications

- encoderless control of synchronous reluctance machines is investigated in collaboration with our partner University of Stellenbosch (South Africa)

☑ final results are available

- a project on encoderless control of induction machines was prepared – funding is granted and project start was in January 2013

☑ first results are expected after 2 – 3 years

- a project on predictive encoderless control is in preparation – funding is expected to start the project hopefully in the second half of 2013

☑ first results are expected after 1 – 2 years

SLED / PRECEDE 2013

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Proposal

October 17 – 19, 2013

Munich, Germany

Thank you !!!