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

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Reasons for Industrial Applications
of Drives with encoderless Control:

• Cost ?? ☹ ??

• Reliability is encoderless (sensorless)
  ✔ resulting in
  ✔ additional cost ???

• Robustness ☻ ✔
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 / controllers
- no additional hardware or additional sensors (e.g., voltage sensors)
- no increased installation effort with respect to parameter adjustment

this was valid from 2000 to 2010
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?

- 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?
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 electronics should not impact
  the performance of encoderless control too much (a certain impact is acceptable)
  ✓ insensitivity with respect to parameter variations
Sensorless (Encoderless) Motor Drives

introduction
• fundamental model methods
• high frequency injection methods

dercoderless 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
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 feasible solution ??
Categories of Machine Models for „Sensorless“ Control

**fundamental models**
- EMF-models, observer
- flux-modulation
- ...

**models based on anisotropies**
- $dq$-inductance
- rotor slotting-effects
- main field saturation
- ...

![Diagram showing stator winding and related equations](image)
**fundamental model**

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

**current injection**

- measuring voltage is high enough
- additional voltage sensors

**high frequency injection**

**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
giving 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
described by 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
  \( \rightarrow \) can we operate the motor itself like a resolver ?

• if the machine itself is a resolver (encoder)
  \( \rightarrow \) 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 $u_c$

elliptic current response $i_c$

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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

\[ i_c \text{ (rotating)} \]
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
Tracking Scheme for Magnetic Anisotropies

\[ i_{cd}^{(F)} = K \cdot \sin(\omega_c t) l_{cq} \]
\[ i_{cq}^{(F)} = -K \cdot \sin(\omega_c t)(l_{cq} - l_{cd}) \Delta \hat{\delta}_a \]
Tracking Scheme for Magnetic Anisotropies

Tracking the estimated angle of the rotor flux by controlling $i_{cq}$ to 0
Encoderless Control Structure

The step response of the PLL; PLL is locked after ca. 10 - 15 ms.
The estimated angle can be used for field orientation as well as for speed or position control of synchronous machines.
Stator Admittance in Complex Plane

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

north and south pole can be distinguished
Injection of 2 Voltage Pulses in $+d$ and $-d$

Evaluate current response

Pulses in $+d$ and $-d$

180° difference

0° difference
Drive with Speed Control
Step Response of Encoderless Position Control
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 WER

- 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
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

works fine !!

further research to be done !!
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 encoderless 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.
Predictive Torque Control

Overview
Predictive Torque Control
Saliency Tracking
Simulation Results
Measurements
Conclusion
Predictive Torque Control

→ Current and PM flux linkage from measurements

→ 7 voltages vectors from inverter

→ prediction of current and respective torque

\[
M = i_s^T J \psi_{pm}^s
\]

→ Selecting optimum of cost function

Overview
Predictive Torque Control
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Predictive Torque Control

→ Discrete model of the machine

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

\[ \Delta \dot{i}_s^s = Y_{\Sigma} \mathbf{u}_L^s \Delta t \]

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

→ Current prediction based on *mean* inverse inductance
Saliency Tracking Approach

Predicted current progression

\[ \Delta \hat{i}_s^s = Y_\Sigma u_L^s \Delta t \]
\[ Y_\Sigma = \frac{1}{2} \left( \frac{1}{L_d} + \frac{1}{L_q} \right) \]

Real current progression

\[ \Delta i_s^s = L_s^{-1} u_L^s \Delta t \]
\[ = Y_\Sigma u_L^s \Delta t + Y_\Delta S(\theta) u_L^s \Delta t \]
\[ Y_\Delta = \frac{1}{2} \left( \frac{1}{L_d} - \frac{1}{L_q} \right) \]
\[ S(\theta) = \begin{bmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{bmatrix} \]

Prediction error

\[ e_{prd}^s = i_s^s - \hat{i}_s^s \]
\[ = \Delta i_s^s - \Delta \hat{i}_s^s \]
\[ = Y_\Delta S(\theta) u_L^s \]
Saliency Tracking Approach

Measured prediction error

\[ e_{prd}^s = i_s^s - \hat{i}_s^s \]

Reconstructed prediction error

\[ e_{prd}^s = S(\theta_{pll})u_L^s \]

PLL controller input

\[ e_{pll} = (i_s^s - \hat{i}_s^s) J S(\theta_{pll})u_L^s \]
Simulation Results for PMSM

Simulation parameter of PMSM

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

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

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole pairs</td>
<td>2</td>
</tr>
<tr>
<td>Nominal power</td>
<td>1.1 kW</td>
</tr>
<tr>
<td>Rated current</td>
<td>3.5 A</td>
</tr>
<tr>
<td>Rated mechanical torque</td>
<td>7 Nm</td>
</tr>
<tr>
<td>Rated electrical speed</td>
<td>314 rad/s</td>
</tr>
</tbody>
</table>

Measurements with Reluctance Machine Data of transverse laminated RM

Overview

Predictive Torque Control

Saliency Tracking

Simulation Results

Measurements

Conclusion
Measurements with Reluctance Machine

Speed controlled step response to 160% rated speed

- Speed [rad/s]
- Torque [Nm]
- Position error [°]
- Time [s]
Measurements with Reluctance Machine

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

- Speed [rad/s]
- Torque [Nm]
- Position error [°]

Measurements with Reluctance Machine
Summary

Proposed Scheme:
- Neglect the saliency in PTC equations
- Prediction error contains angle information
- Reconstruct Prediction Error using PLL angle
- Vector product 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 $\rightarrow$ voltage margin $\rightarrow$ 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
Encoderless Control with Arbitrary Injection

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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 !!!
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
  \[\rightarrow \text{voltage sensors} \text{ are necessary} \] !!!
- it is possible to use current derivatives
  instead of motor voltages
  \[\rightarrow \text{measuring current derivatives, however,} \]
  by \textit{standard current transducers} is not really possible
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 pulses 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
Current Derivative Sensors as used at the University of Malta
Coax Sensor Responses as measured at the University of Malta

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%

ramp from 0 - 1.4 A is applied in 20 μs
Coaxial Coils as used at Wuppertal University
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

\[ u = L \frac{di}{dt} \]

• \( \rightarrow \) 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 ???
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
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

• → 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

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

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

$u_c = u_c \cos(\omega_c t)$
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
Thank you !!!