

SENSORLESS CONTROL OF
PM SYNCHRONOUS MACHINES
BY EVALUATION OF dI/dt - MEASUREMENTS

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- Theoretical background of dI/dt measurements
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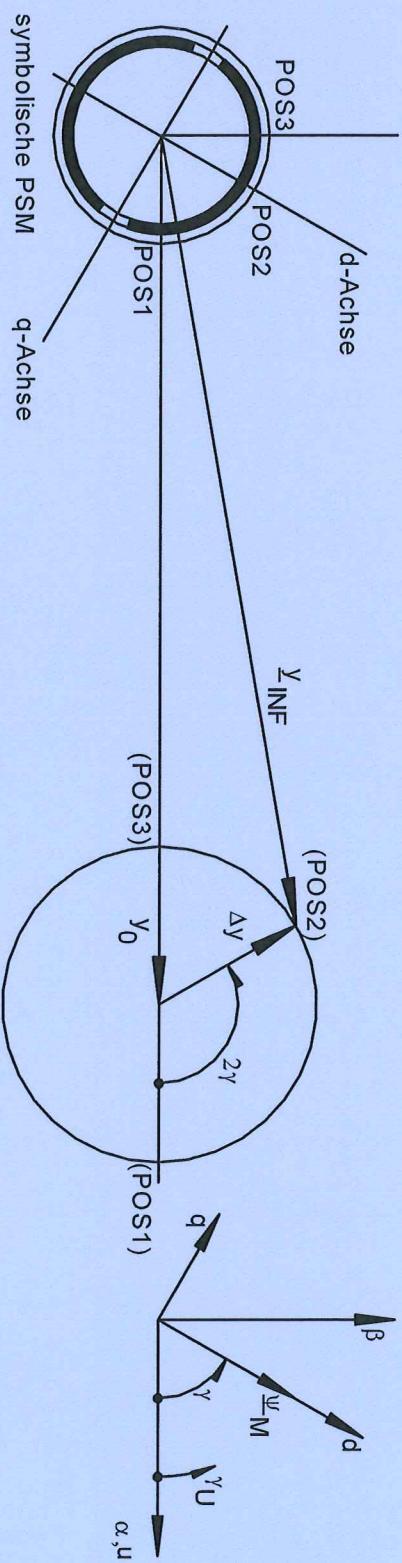
THEORETICAL BACKGROUND

- Basic idea of dI/dt -evaluation

Applying a voltage test phasor

Measuring the dI/dt -reaction (current change)

We find an angular dependence of $\underline{Y}_{\text{INF}} = d\underline{I}/dt$ due to different inductances in d- and q-axis
 $\underline{Y}_{\text{INF}}$ depends on DOUBLE the angular position 2γ (we cannot distinguish between north- and south-pole)
Hence, we can principally calculate 2γ from current changes, e.g. using INFORM method

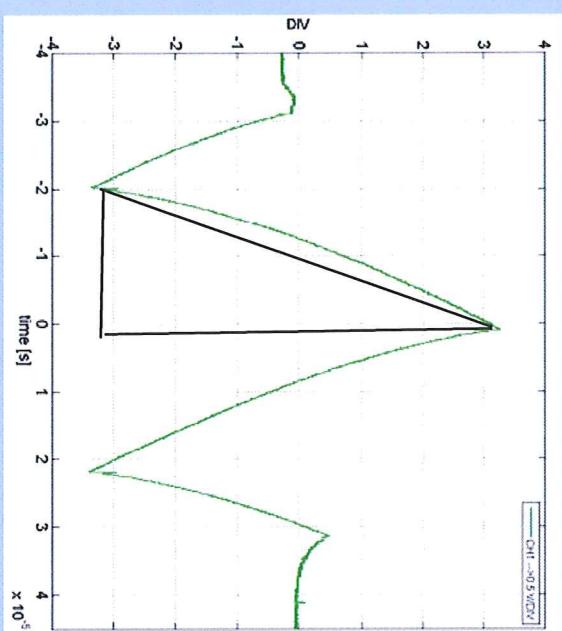


THEORETICAL BACKGROUND

- Example of a practical dI/dt -measurement
- According to INFORM® method

INFORM® .. INdirect Flux detection by On-line Reactance Measurement

Small signal change of current (green line) is measured
Operating point of current (and hence torque) remains unchanged – no considerable torque ripple



Measuring dI/dt as a small signal change of current
in one phase

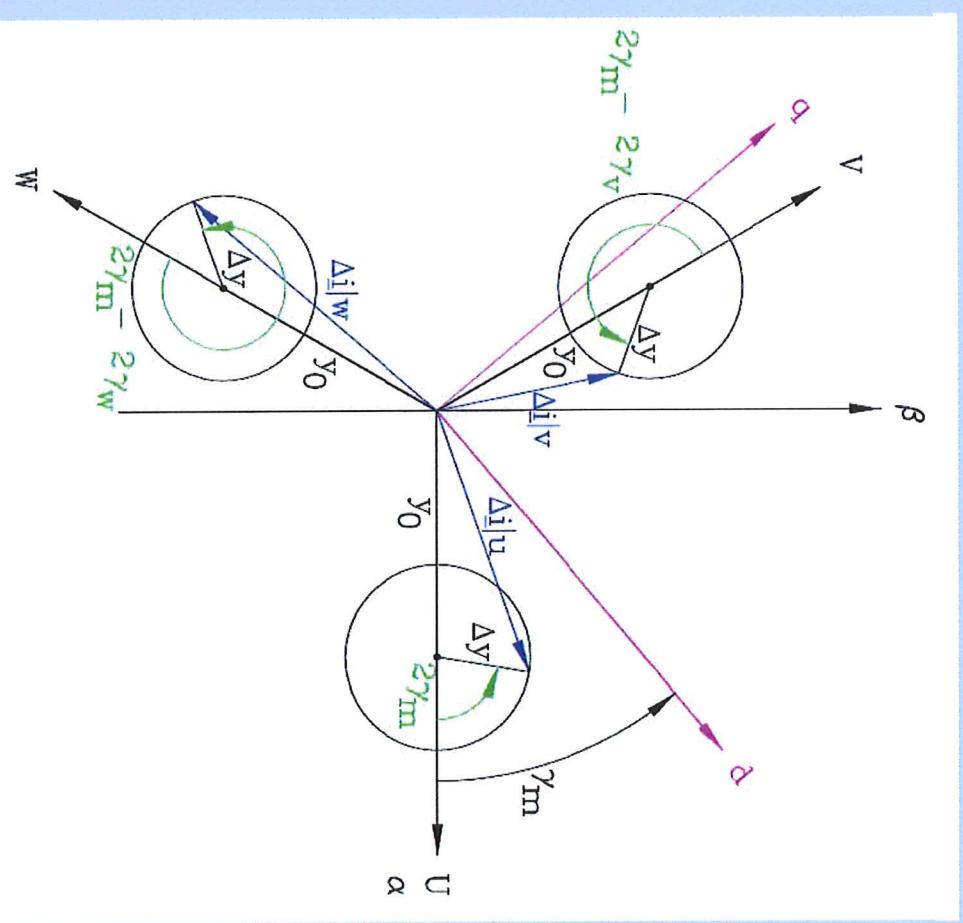
THEORETICAL BACKGROUND

- Combining INFORM measurements with different test voltage directions

Applying different voltage test phasors
Measuring the respective di/dt -reactions

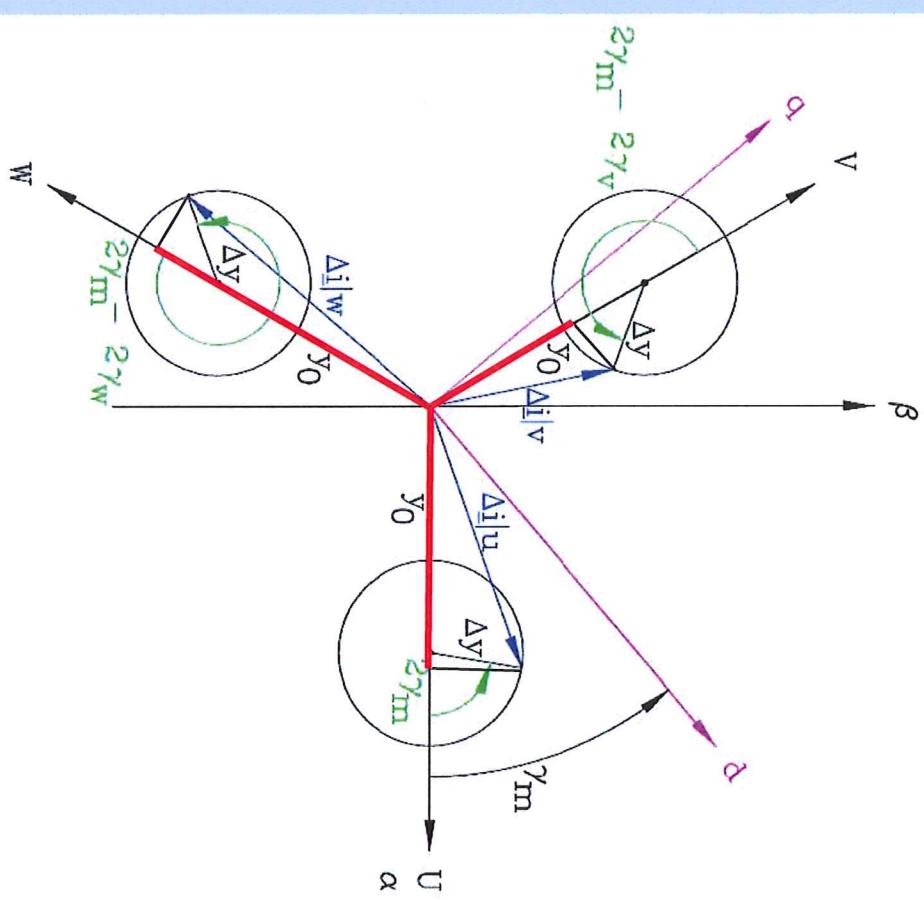
We obtain up to 6 equations for the 3 variables y_o , Δy and 2γ (if we use 3 test voltage directions)

Different evaluations with a subset of these equations are possible



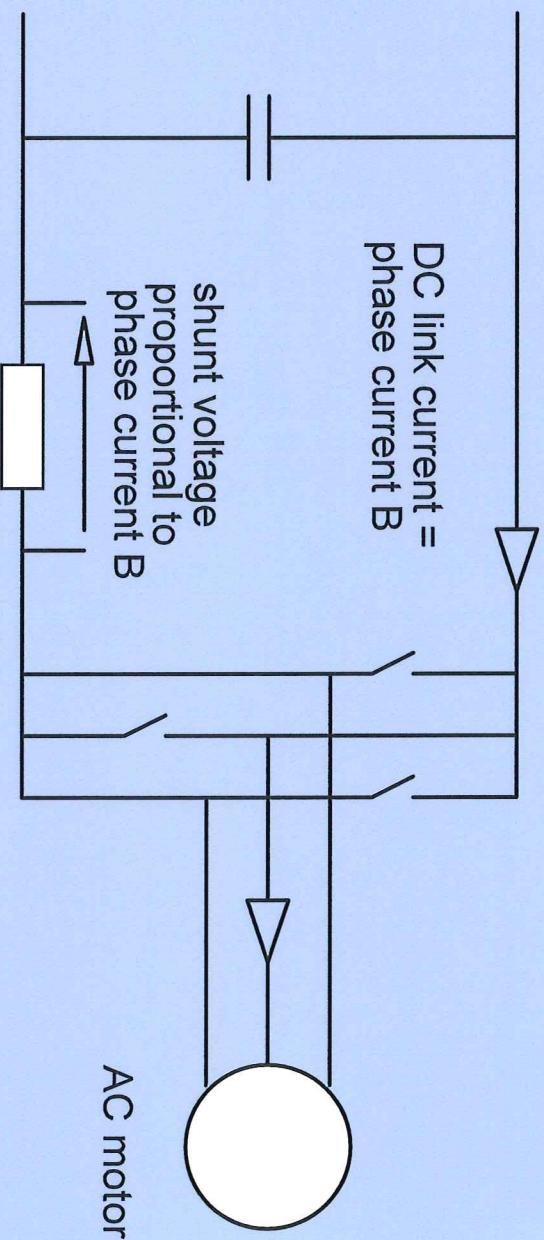
- Example: Using subset of 3 di/dt-measurements:
- „Real part evaluation“
(only phase currents in test voltage directions are used)

Measuring only the phase current changes in test voltage directions (the thick red lines in the picture) yields enough information for calculating 2γ .



- Using subset of 3 di/dt-measurements „Real part evaluation“ – necessary inverter hardware structure

An important advantage of the INFORM-variant „Real part evaluation“ is the simple inverter structure (according to the following figure). Measuring only the DC link current is sufficient for evaluation, since the DC link current is ALWAYs the phase current in test voltage direction. (Of course, a normal phase current measurement or a 3-shunt measurement between lower transistors and DC minus potential is also possible)



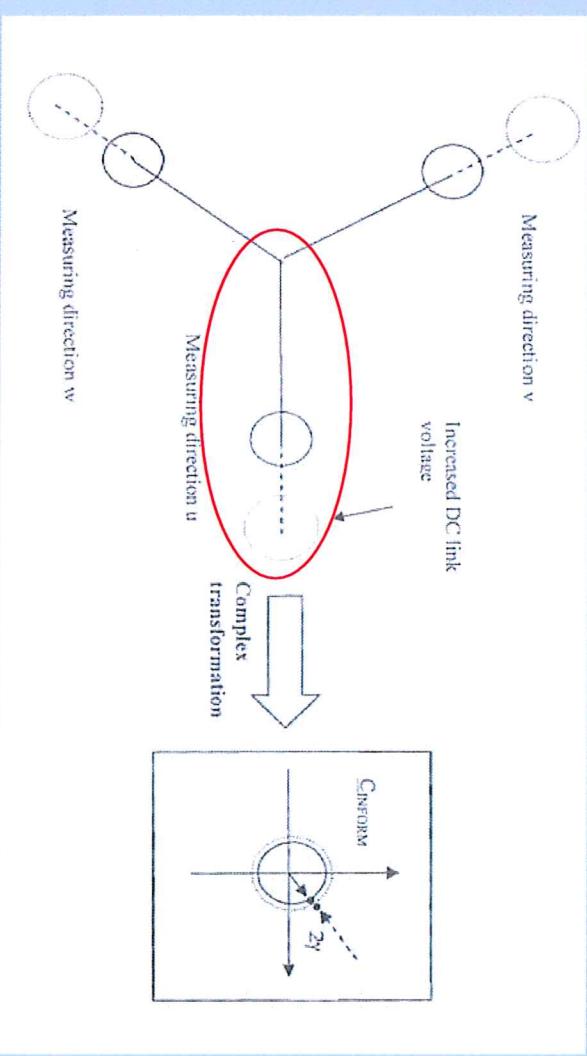
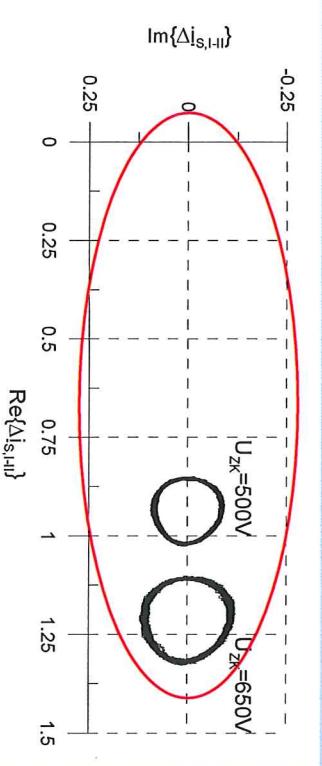
- Insensitivity of INFORM measurements to varying DC link voltages

In the following figure, the 3 current-change-circles (at varying angular position γ) are shown. Two such triples are given at different DC link voltage levels (100% and 130% U_{DC}).

By using a complex linear transformation of the equations representing the current change circles, an offset-free „characteristic INFORM curve C_{INFORM} “ is obtained. The argument of this curve is double the rotor angular position 2γ . This argument is NOT INFLUENCED by varying DC link voltage.

Current change circles at two different DC link voltages. Right figure: theory (including transformed curve C_{INFORM}).

Figure below: y-measurements at DC link voltages of 500 V and 650 V.

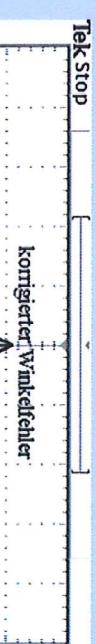
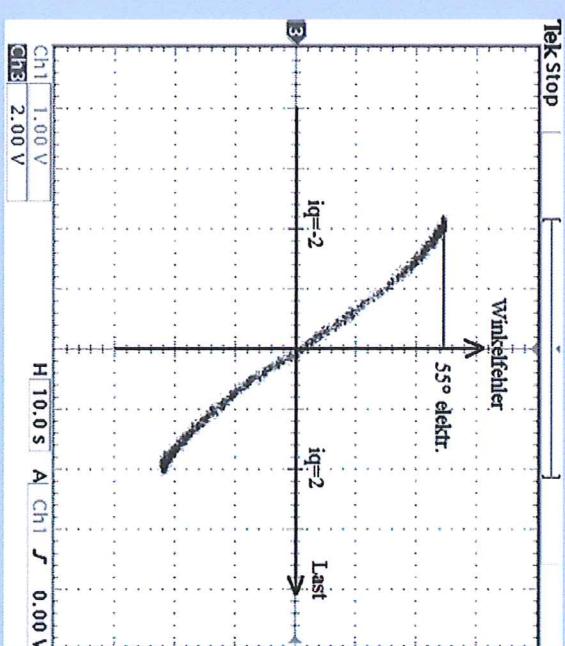


THEORETICAL BACKGROUND

- Load dependence and correction of
INFORM-measured rotor position

At load, the q-current has influence on the whole flux density distribution in the PMSM. Hence, the axis of minimum inductance is shifted from the d-axis more or less to the q-axis.

Since this effect depends on the (well-known) q-current, it can be compensated by a q-current-dependent correction angle $\Delta\gamma(i_q)$.



Right figures:

Upper figure: Angular displacement of 55° (el.) at $i_q = 2$

Lower figure: Angular displacement of ~0° (el.) after correction

THEORETICAL BACKGROUND

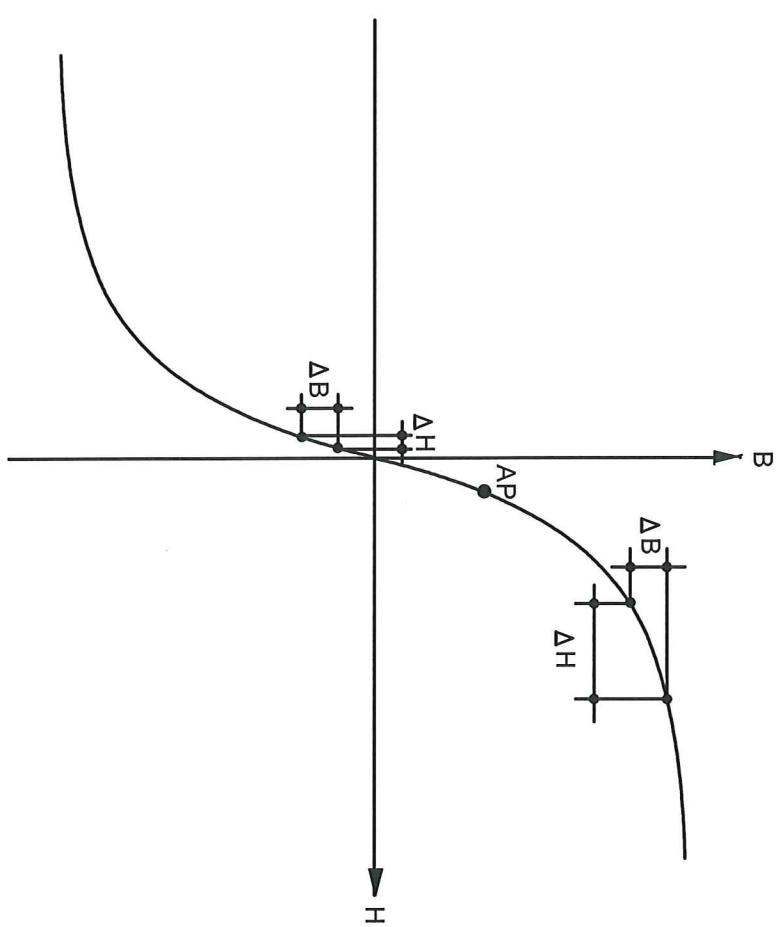
- Initialization by a „Start INFORM sequence“
 - -yields initial position γ_0

By shifting the magnetic set point in the PMSM, we can distinguish between field-increasing and field-decreasing current component.

In case of field-increasing current (positive d-) component – di/dt -measurement yields increased current change (smaller inductance due to saturation)
In case of field-decreasing current (negative d-) component – reduced saturation, hence reduced current change

-Criterion for eliminating the ambiguity of small-signal INFORM

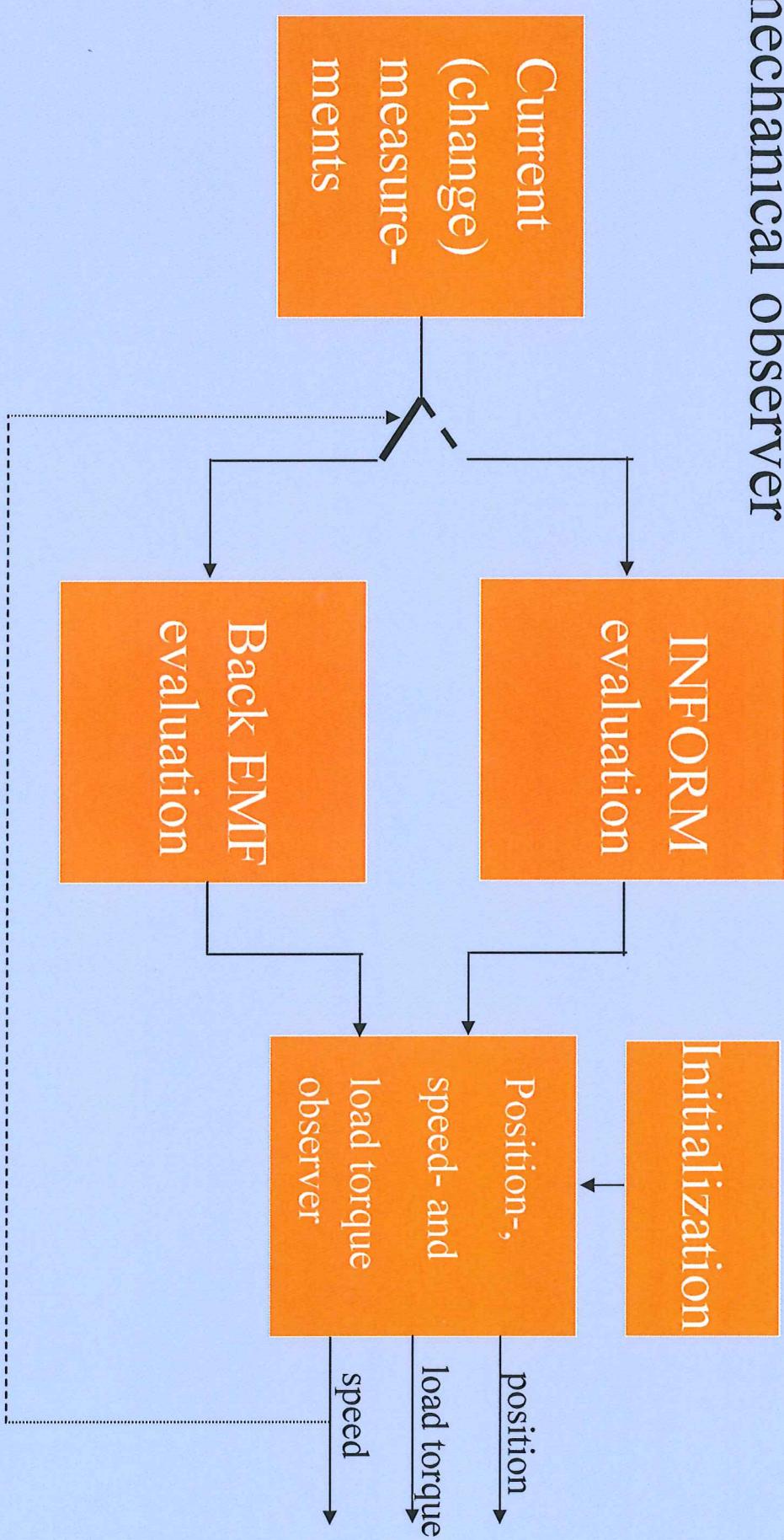
Procedure takes only a few milliseconds
No movement of the rotor



STRUCTURE OF SENSORLESS CONTROL

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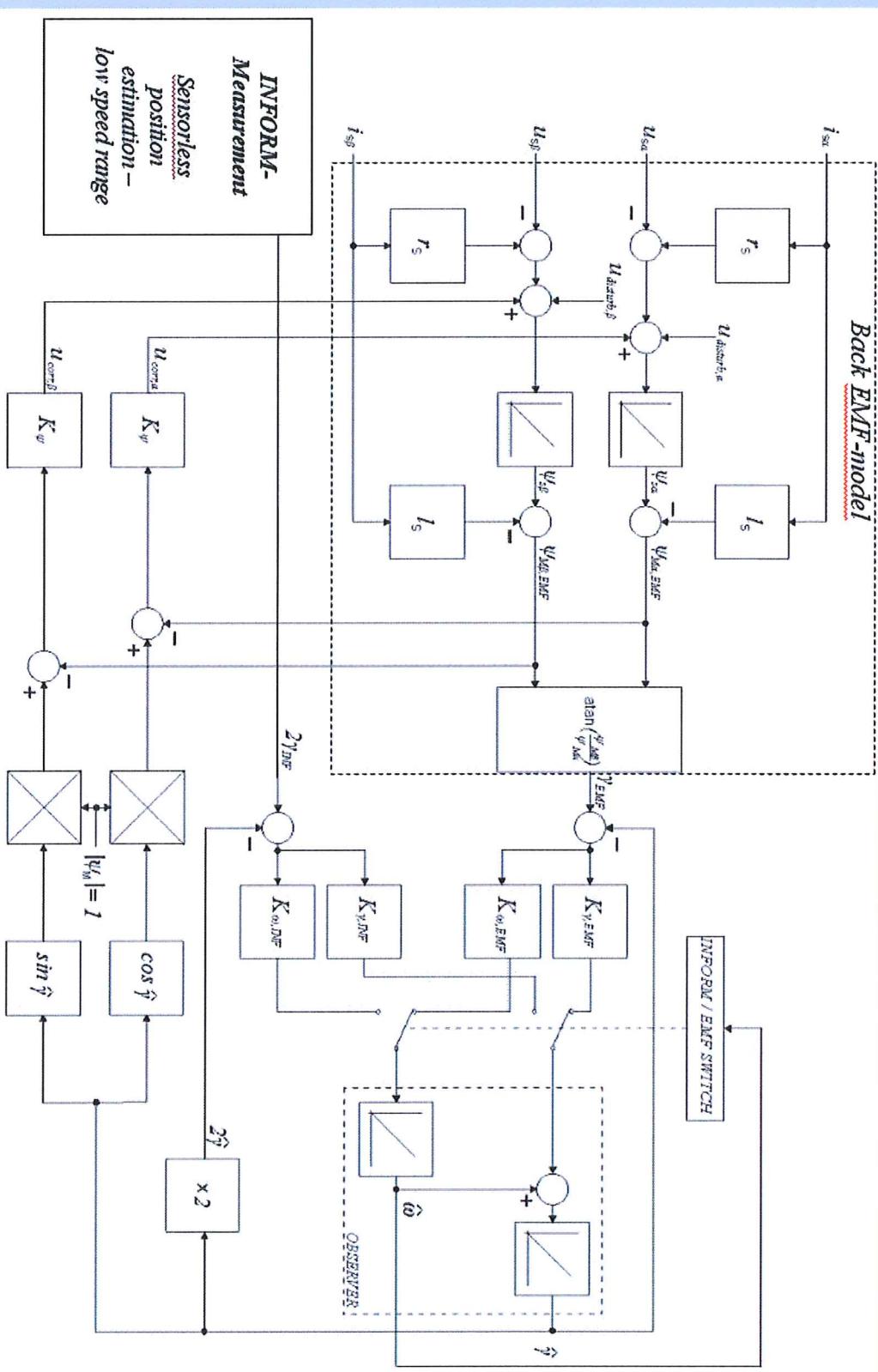
Combining INFORM- and Back EMF evaluation with mechanical observer



STRUCTURE OF SENSORLESS CONTROL

Structure of INFORM – BackEMF – observer interaction

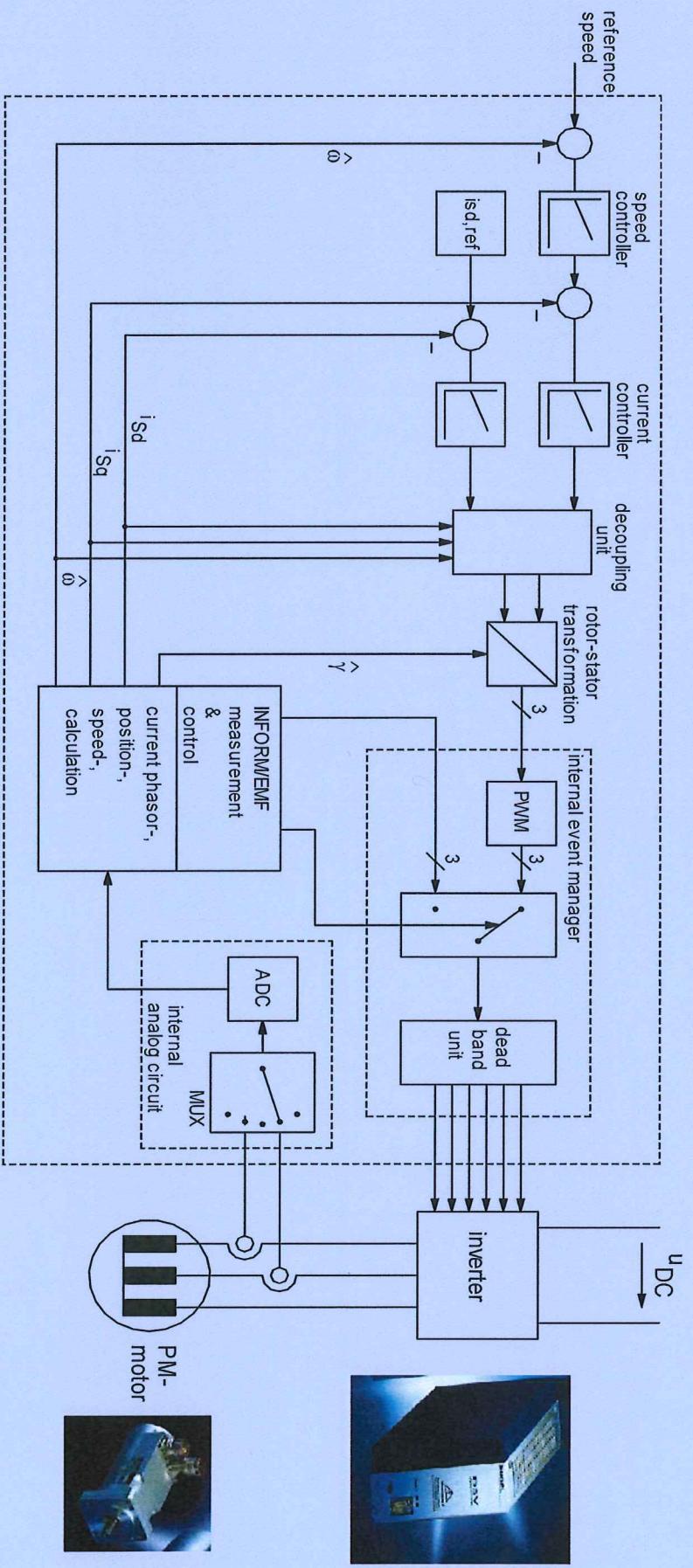
Sensorless
position
estimation –
low speed range



STRUCTURE OF SENSORLESS CONTROL

Hardware and software structure

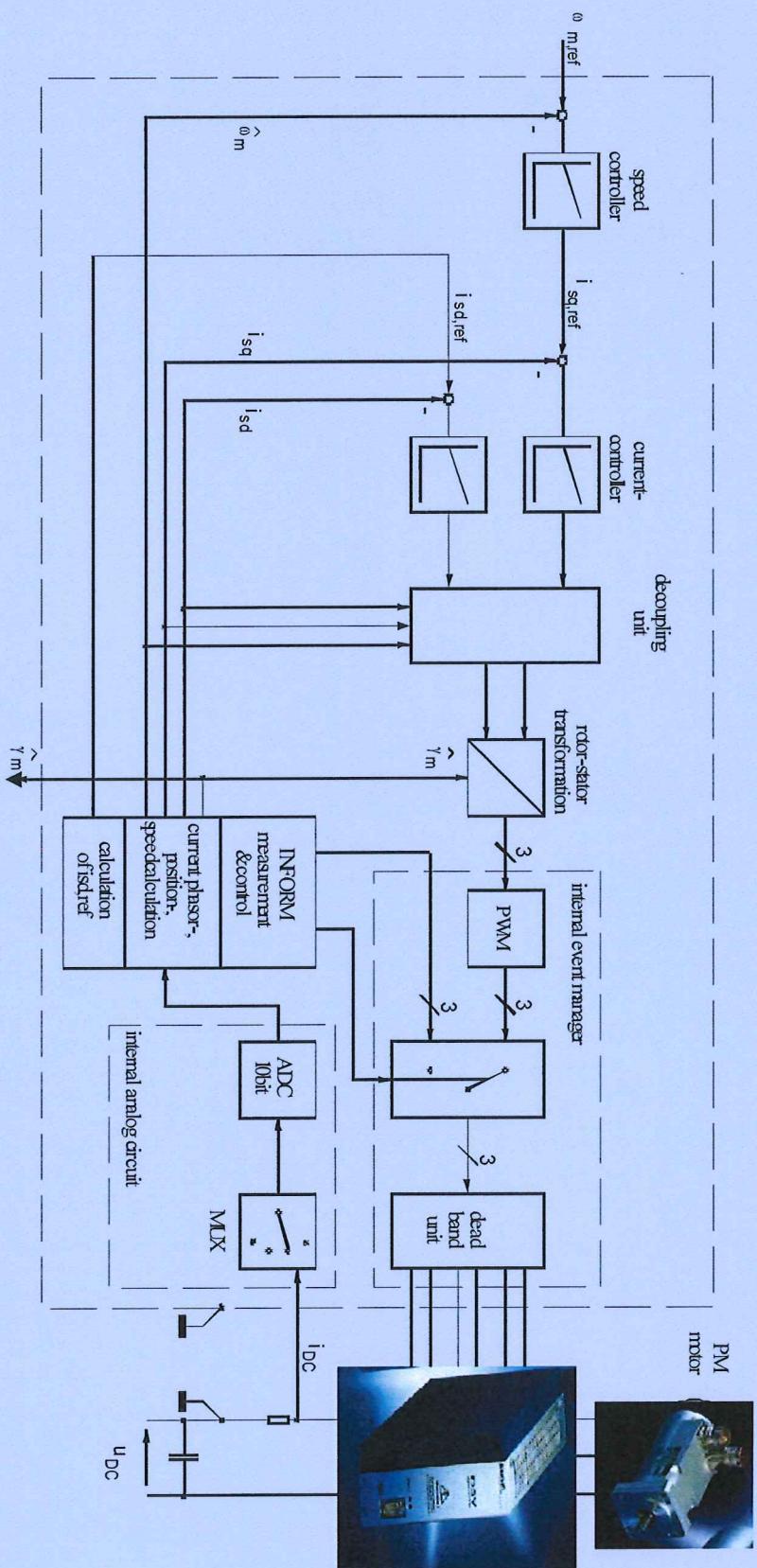
Variant: „Phase current measurement“



Speed-controlled system based on phase current measurements with high starting torque
Necessary hardware: 16 bit fixed-point arithmetic, 10 bit ADC, conversion time about 1 μ s

STRUCTURE OF SENSORLESS CONTROL

Hardware and software structure Variant: „DC link current measurement“



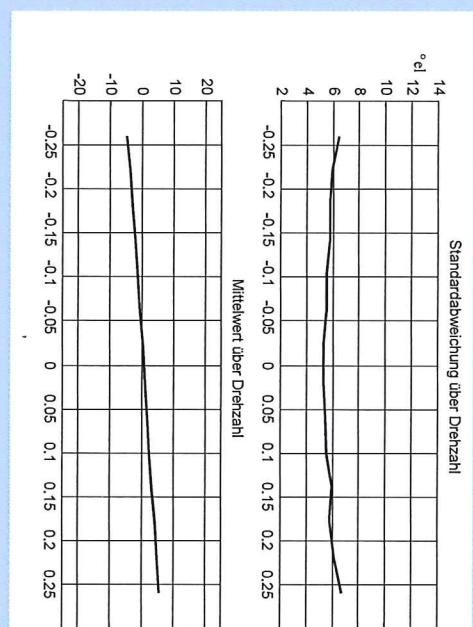
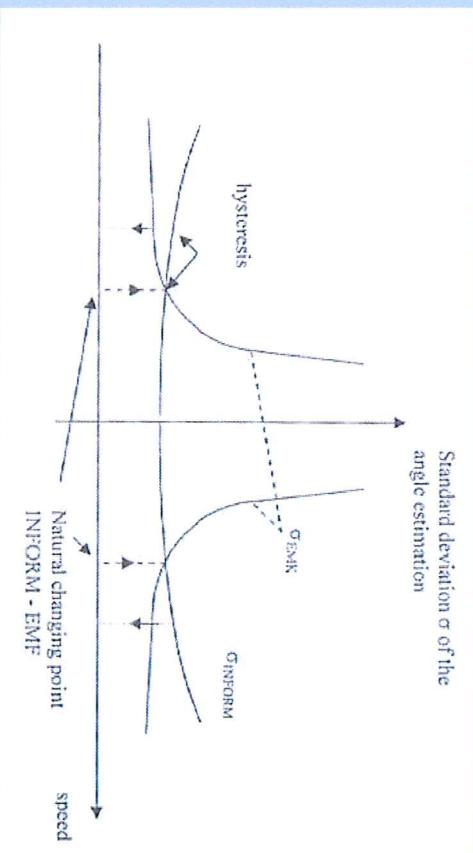
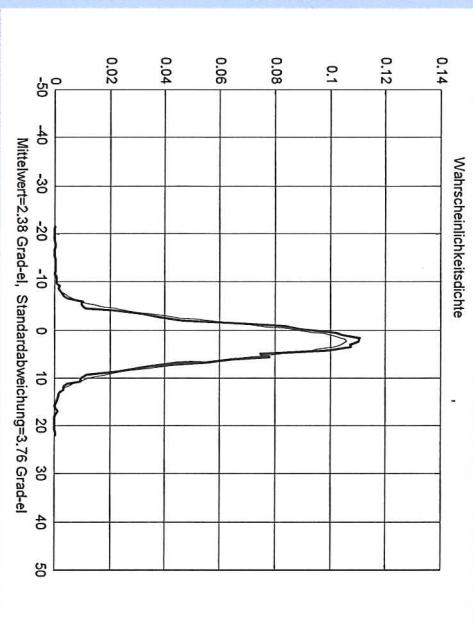
Speed-controlled system based on DC link current measurement with high starting torque
 Necessary hardware: 16 bit fixed-point arithmetic, 10 bit ADC, conversion time about $1\mu s$
 Important: Highly dynamic DC link current measurement (measurement valid within $\sim 3\mu s$)
 Recommended: Analog ground of DSP connected to negative DC link potential

RESULTS OF SENSORLESS CONTROL

Expected accuracy of INFORM method

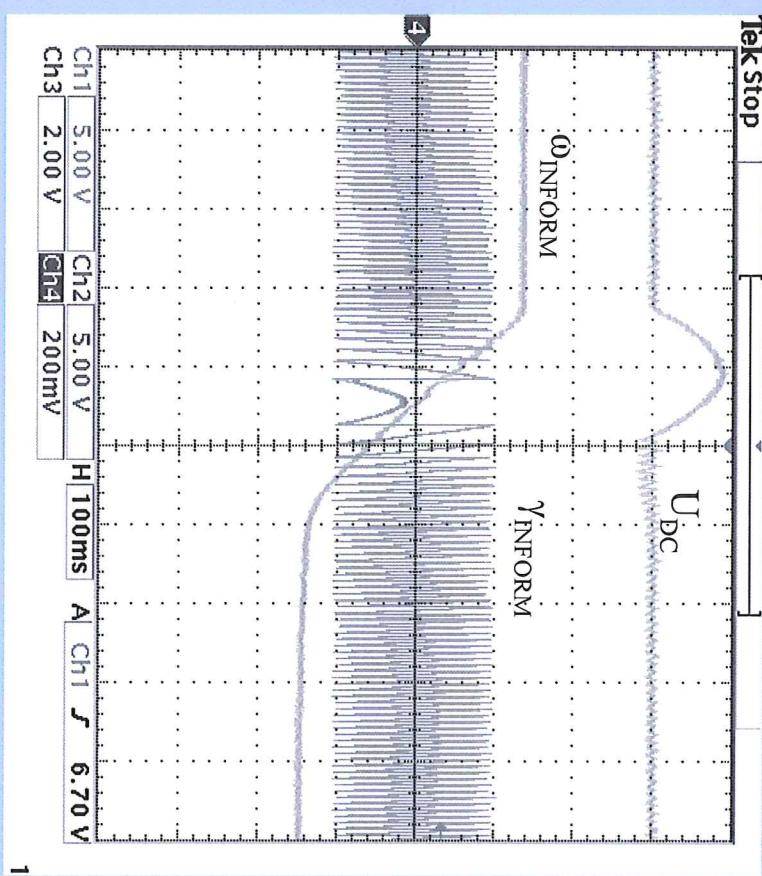
INFORM-detected rotor position is more or less Gaussian-distributed around the measurement value. Typical standard deviations of angular error are between $2^\circ(\text{el.})$ and 10° . In the figure below an "INFORM-friendly" motor with about 3° standard deviation is shown. As shown in the right picture, the angular error increases slightly with speed. The systematic error is due to calculating and measuring dead times and can be compensated.

The last picture shows the natural switching point between INFORM and the back EMF evaluation. The latter goes to infinity at zero speed. At a certain speed, both INFORM and BackEMF error are equal. At this point the methods should be changed.

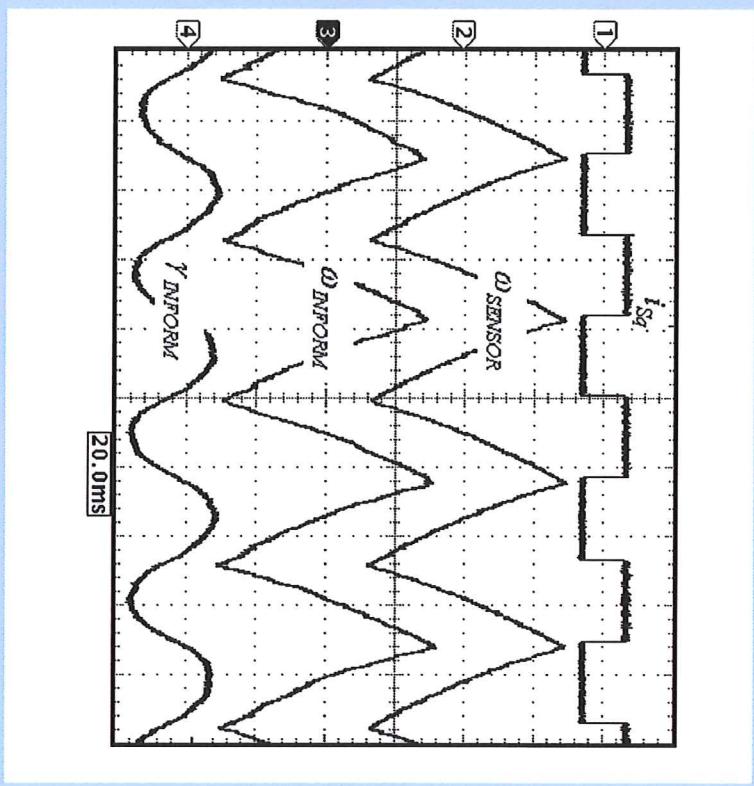


RESULTS OF SENSORLESS CONTROL

Examples of the dynamic behaviour of the sensorless system



DC link voltage U_{DC} (30% transient increase during generative breaking), estimated angular velocity (ω_{INFORM}) and estimated angular position γ_{INFORM} based on INFORM measurements during a speed reversal of $\omega=0.7$ to $\omega=-0.7$.



Dynamic behaviour of estimated angular position and estimated angular velocity of a torque-controlled PSM (in the Figure: rated current, \pm half of rated speed, angular position: 180 %unit)

APPLICATION EXAMPLES OF INFORM DRIVES

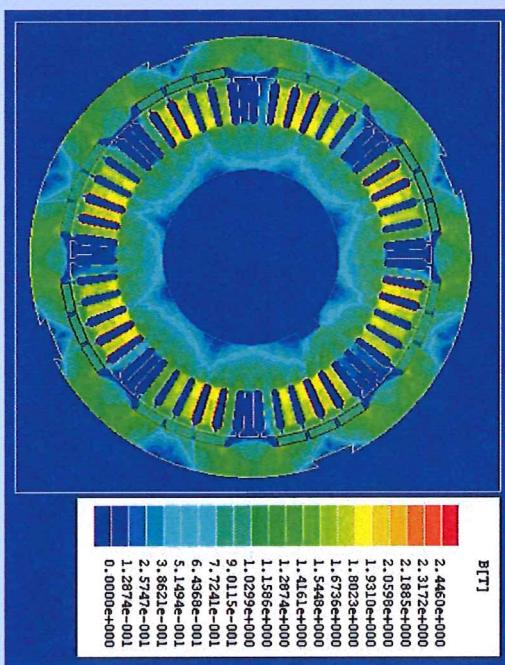
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Application example: 250 Nm Starter Generator

Outer rotor motor / generator

Advantage of PMSM: larger air gap, more compact, higher efficiency

Right hand side: FEM calculation of outer rotor machine



Start up with INFORM method at -30° C

12 V automotive voltage

Up to 700 A starting current

250 Nm starting torque

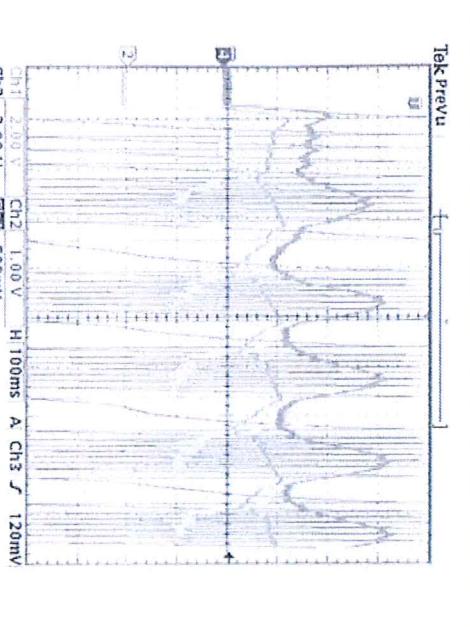


Abbildung 5: CH1: q gest (200mA/Div), CH2: u250start (10mV, 5ms Glättung), CH3: ugec e (45mV/Div), CH4: omidach (75mV-1/Div)

APPLICATION EXAMPLES OF INFORM DRIVES

Application example: 500 Nm Traction drive

TU Vienna supports

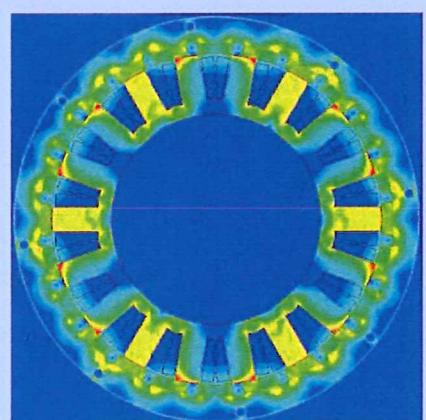
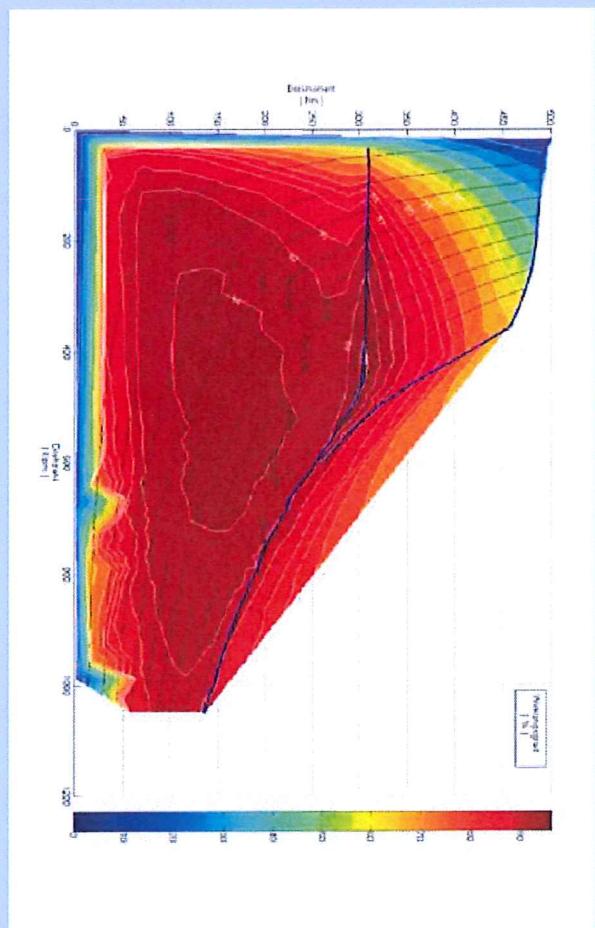
FEM design, construction,

Building up of prototypes
laboratory test stand



Outer rotor motor with tooth coils

High efficiency up to 95%



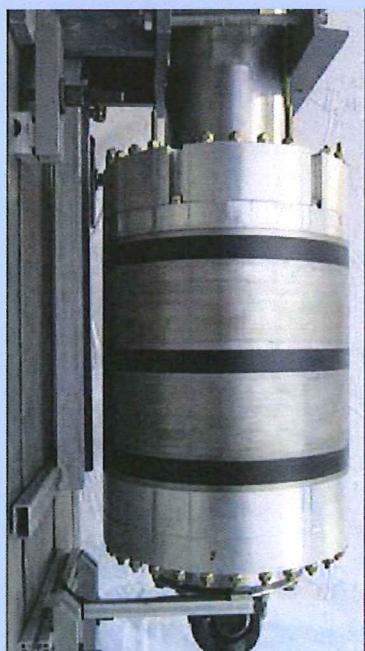
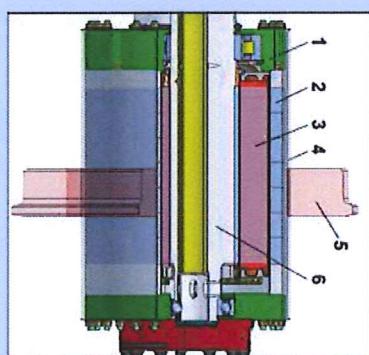
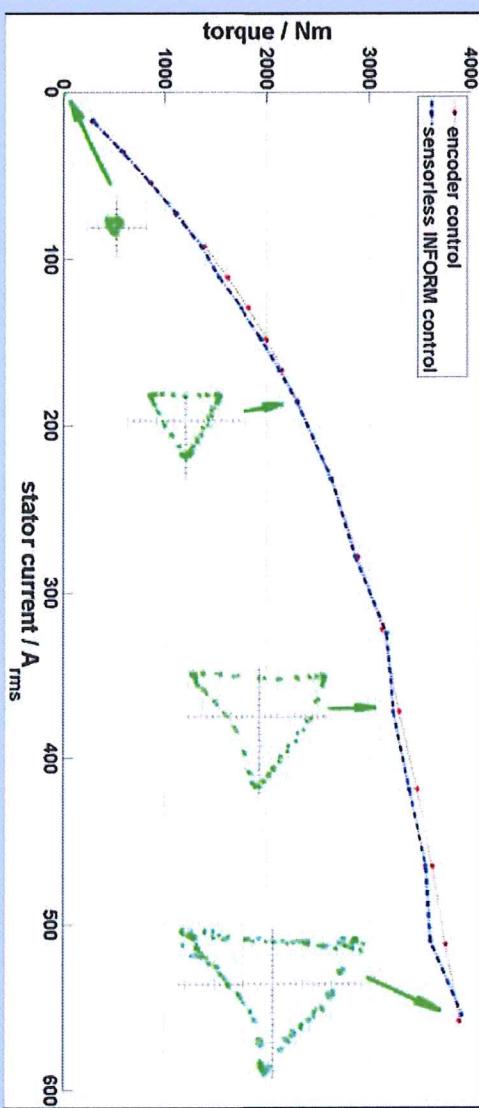
APPLICATION EXAMPLES OF INFORM DRIVES

Application example: 3000 Nm Railway traction drive

TU Vienna supported construction, building up of 3000 Nm / 1.000 rpm prototypes and lab test stand

Right curve shows sensor-based and sensorless control up to 4000 Nm, almost same behaviour

Furthermore, the characteristic INFORM curves up to 3xrated current are shown.



APPLICATION EXAMPLES OF INFORM DRIVES

Application example: 0.5 kW / 230 V handheld tool

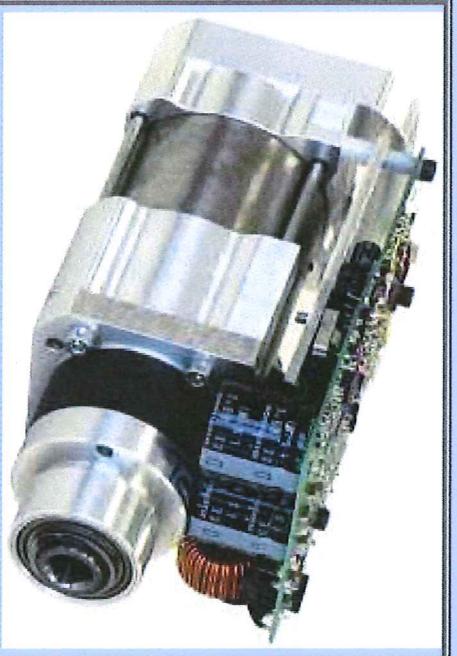
Compact inner rotor PMSM drive with integrated power electronics

16 bit DSP with analog ground connected to negative DC link potential.

Current measurement via 3 ohmic shunts between IGBTs and negative DC link.

Antriebssystem für handgeführtes Werkzeug

Dargestellt ist ein Getriebeantrieb basierend auf den Standardprodukten BSR3750 und GP56. Gewicht zu sparen wurde in dieser Ausführung auf das Druckgußgehäuse des Motors verzichtet. Das Getrieb wurde auf mit einer Polygon-Innenverzahnung nach DIN32711 ausgeführt. Der ebenfalls kundenspezifisch realisierte digitale Umrichter betreibt den Motor im sensorlosen "INFORM"- Betrieb nach Prof. Schrödl.



APPLICATION EXAMPLES OF INFORM DRIVES

Application example: 20 Nm/ 200 rpm brushing drive

PMSM with gear box (diameter <63mm) speed 0-200 rpm, torque up to 22 Nm (red ellipse)

Inverter with phase current measurement (red circle)

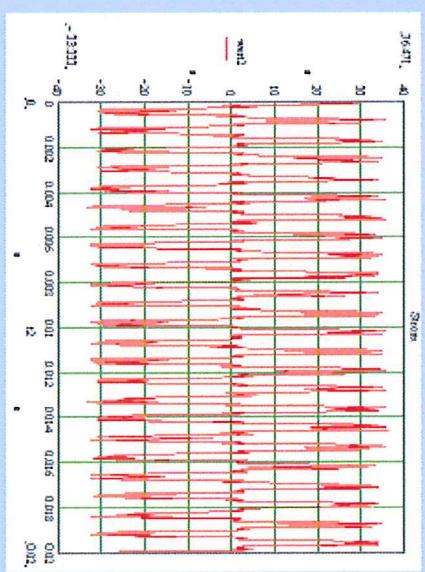
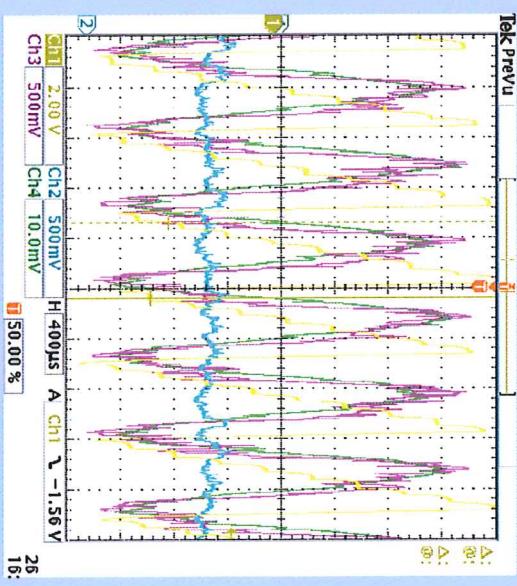
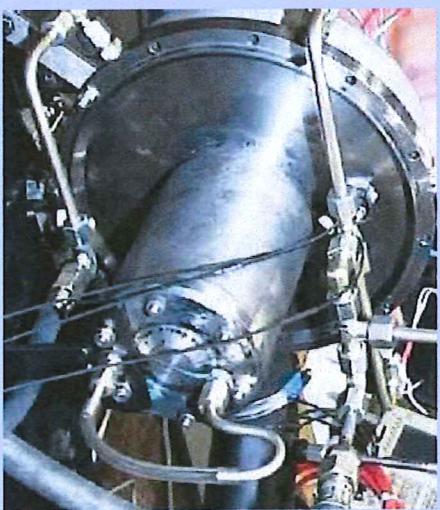
Application: Brushing away colour particles from printing machine cylinders in harsh environment, full torque from standstill.



APPLICATION EXAMPLES OF INFORM DRIVES

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Application example: 10 kW / 100.000 rpm drive



High speed aggregate in automotive application.
High axial forces, hence risk of damaging beyond
100.000 rpm. Sinusoidal operation necessary at high
speed due to high rotor losses.

APPLICATION EXAMPLES OF INFORM DRIVES

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Application example: 10 kW / 100.000 rpm drive

Destructive test beyond maximum speed



APPLICATION EXAMPLES OF INFORM DRIVES

Application example: Top-quality dental drive

(0-) 100 - 40.000 rpm

Ultra compact

PMSM with air gap
winding and

cylindrical rotor,
hence almost no
reluctance.

Operating range
from 100 rpm (endo
applications) to
40.000 rpm (up to
200.000 rpm in other
products)

The advertisement features a woman's face with green floral patterns. On the left, a dental handpiece is shown with several interchangeable burs. The text includes:
KaVo COMFORTdrive 200 XD
Leistung, die alle Ansprüche erfüllt – und Ihre Erwartungen übertreift.
Erleben Sie die Kraft einer Innovation.
Von Anfang an zu Ende gebracht.
Jede Menge Leistung bei konstanter Laufzeit.

SMARTdrive
INFORMATION TECHNOLOGY
So sanft kann Kraft sein.

KaVo. Dental Excellence.

CONCLUSION

- The report deals with sensorless control of PMSMs based on di/dt-measurements
- di/dt-evaluation according to INFORM method was described
- A theoretical background was given.
- The recommended hardware and software structure was presented.
- Some representative measurements were shown.
- Typical application examples (prototypes and series products) were discussed.
- As a summary and outlook, it can be stated that di/dt-based sensorless control methods are suitable for industrial series production.