Sensorless Control

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  - Speed reversal at low speed. Load Impact at zero speed
- Field Oriented Sensorless Control with High Frequency injection for Matrix Converters
  - Matrix Converter linearization
  - Speed reversal at low speed. Load Impact at zero speed
- Conclusions
Introduction

Motivation for Sensorless Control

- Aim for Sensorless Control:
  - Dynamic control of electrical machines without need for position encoder
  - No encoder and no associated electronics
    - Volume and cost reduction
    - Increases reliability (fault tolerant, redundancy)
Introduction
Different Sensorless Techniques

- Use of machine model critical at low speeds:
  - Voltage distortion high (deadtime, noise, A/D resolution).
  - Parameter variation (temperature, saturation) influences accuracy and stability.
- Use of saliencies combined with test signals (either pulses or HF) makes position estimation possible without requiring machine model
  - Impedance contains position information.
  - Independent of machine parameters.
  - Sensorless vector control possible, including zero speed.
Dynamic Model & Injection methods

- Stator flux estimator in the alpha-beta frame for PMSM
  - integrator drift due to DC offsets in the measured quantities
  - accumulated numerical error.

- MRAS (Model based Reference Adaptive System) and Observers are used to improve the position estimation
  - integrator drift remains a difficulty
  - high noise content of the voltage
  - at very low speeds there is a lack of back-emf and the PMSM has an inherent unobservability

- Injection methods, either High Frequency or Test pulses, are a good solution. However, there are three main disadvantages:
  - They introduce extra losses
  - Limited Speed range
  - The position estimates may contain ripples that arise from
    - Multiple saliences
    - non-sinusoidal distribution of the saliency
    - inverter non-linearity (deadtime and voltage drop)
Machine Saliency. HF Injection

- Based on injecting a HF voltage, obtaining a HF current with rotor position information.
  - Two position signals are obtained.

\[
\begin{bmatrix}
V_{\alpha i} \\
V_{\beta i}
\end{bmatrix} = \begin{bmatrix}
-\sin(\omega_i t) \\
\cos(\omega_i t)
\end{bmatrix} \hat{V}_i = 20 \text{ V} \\
\omega_i = 1 \text{ kHz}
\]

Compensated Position Signals

Homodyne Signal Processing
Machine Saliency. Test pulse

- Voltage test vectors correspond to the six non-zero switching states of a voltage source inverter.
- Test vectors are applied in equal and opposite pairs – they do not effect fundamental excitation.
- Disadvantage:
  - Require an additional sensor, however this can be integrated drive.

\[ v_1, v_4 \] 
\[ v_3, v_6 \] 
\[ v_5, v_2 \]
• Introduction
  • Motivation for Sensorless Control
  • Different Sensorless Techniques

**Machine Saliency. Magnetic saturation**

• Field Oriented Sensorless Control with voltage pulse test for Matrix Converters
  • Position Signals for Matrix Converters
  • Speed reversal at low speed. Load Impact at zero speed

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• Conclusions
Machine Saliency

- An AC machine is said to be salient if the Inductance has a changing value. In the d/q model, a saliency machine implies $L_d \neq L_q$.

- Types of Saliency
  - Geometrical (Typical in the IPM)
  - Saturation (Magnetic or Leakage Inductance)

- In SMPMSM, the geometric saliency is very small. Therefore, it is tracked the saturation saliency.

\[
\begin{align*}
    \begin{bmatrix}
        v_a \\
        v_b \\
        v_c
    \end{bmatrix}
    &=
    r_s
    \begin{bmatrix}
        i_a \\
        i_b \\
        i_c
    \end{bmatrix}
    +
    \frac{d}{dt}
    \begin{bmatrix}
        l_a & M_{ab} & M_{ac} \\
        M_{ba} & l_b & M_{bc} \\
        M_{ca} & M_{cb} & l_c
    \end{bmatrix}
    \begin{bmatrix}
        i_a \\
        i_b \\
        i_c
    \end{bmatrix}
    +
    \psi_m
    \begin{bmatrix}
        \cos(\theta) \\
        \cos(\theta - \frac{2\pi}{3}) \\
        \cos(\theta - \frac{4\pi}{3})
    \end{bmatrix}
\end{align*}
\]
Machine Saliency

- Sinusoidal variation of the stator phase inductance as function of the rotor position.

\[
l_a = l_0 - l_\Delta \cos(2 \cdot P \cdot \theta)
\]

\[
l_b = l_0 - l_\Delta \cos(2 \cdot P \cdot (\theta - 2\pi/3))
\]

\[
l_c = l_0 - l_\Delta \cos(2 \cdot P \cdot (\theta - 4\pi/3))
\]

- For example (P=1)

\[
l_a = l_0 - l_\Delta \cos(2 \cdot 0^\circ) = l_0 - l_\Delta
\]

\[
l_a = l_0 - l_\Delta \cos(2 \cdot 45^\circ) = l_0
\]

\[
l_a = l_0 - l_\Delta \cos(2 \cdot 90^\circ) = l_0 + l_\Delta
\]
Magnetic Saturation

- Further increase in magnetic field strength (H) will result in no further change in magnetic flux density (B).
- Same material has different permeability ($\mu$) → different inductance ($l_a$)

\[
\mu = \frac{dB}{dH}; \quad l_a = \mu \frac{N^2 A}{l};
\]

N → turns; A → Section; l → length

\[
l_a = \frac{v_a}{di_a/dt};
\]
How to measure the inductance?

- The Converter imposes a known voltage ($v_a$)
- The $\frac{di_a}{dt}$ must be measured. A Rogowski Coil will be used

$$l_a = \frac{v_a}{\frac{di_a}{dt}}$$

- A Rogowski coil is an 'air-cored' toroidal coil placed round the conductor. The alternating magnetic field produced by the current induces a voltage in the coil which is proportional to the rate of change of current. The direct output from the coil is given by $V_{out} = M \frac{di}{dt}$ Where $M$ is the mutual inductance of the coil and $\frac{di}{dt}$ is the rate of change of current.
Machine Saliency

\[ l_a = l_0 - l_\Delta \cos(2 \cdot 0^\circ) = l_0 - l_\Delta \]

\[ l_a = l_0 - l_\Delta \cos(2 \cdot 45^\circ) = l_0 \]

\[ l_a = l_0 - l_\Delta \cos(2 \cdot 90^\circ) = l_0 + l_\Delta \]

Saturation

\[ \frac{di_a}{dt} = \frac{V}{l_0 - l_\Delta} \]

\[ \text{slope } \frac{V}{l_0 - l_\Delta} \]

\[ \frac{di_a}{dt} = \frac{V}{l_0} \]

\[ \text{slope } \frac{V}{l_0} \]

\[ \text{slope } \frac{V}{l_0 + l_\Delta} \]
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• Conclusions
Position Signals for MC
Double sided PWM SVM pattern

- Test Pulse Signal
  - PWM pattern modification. Where?
  - Duration?
  - Amplitude?
    - Large
    - Medium
    - Small
**Position Signals for MC**

**Double sided PWM SVM pattern**

---

**End of SVM sector 1**

<table>
<thead>
<tr>
<th>$U_C$</th>
<th>$U_A$</th>
<th>$U_B$</th>
<th>$U_C$</th>
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<tbody>
<tr>
<td>$\delta_{03/2}$</td>
<td>$\delta_1/2$</td>
<td>$\delta_2/2$</td>
<td>$\delta_{02/2}$</td>
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<tr>
<td>$\delta_3/2$</td>
<td>$\delta_{01/2}$</td>
<td>$\delta_{02/2}$</td>
<td>$\delta_2/2$</td>
</tr>
<tr>
<td>$\delta_{01/2}$</td>
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<td>$\delta_2/2$</td>
<td>$\delta_{01/2}$</td>
</tr>
</tbody>
</table>

**Small / Medium / Large voltage pulse test**

- $V_{aN}$
- $V_{bN}$
- $V_{cN}$
- $V_{Nn}$
- $V_{an}$
- $V_{bn}$
- $V_{cn}$

**$di/dt$ 1st measure**

**$di/dt$ 2nd measure**
### Position Signals for MC

#### Double sided PWM SVM pattern

<table>
<thead>
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<th>Small / Medium / Large voltage pulse test</th>
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<tbody>
<tr>
<td>$u_c \rightarrow u_A$</td>
</tr>
<tr>
<td>$u_A \rightarrow u_B$</td>
</tr>
<tr>
<td>$u_B \rightarrow u_A$</td>
</tr>
<tr>
<td>$u_A \rightarrow u_c$</td>
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<th>$U_B$</th>
<th>$U_A$</th>
<th>$U_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_{O1}/2$</td>
<td>$\delta_{I1}/2$</td>
<td>$\delta_{O1}/2$</td>
<td>$\delta_{I1}/2$</td>
<td>$\delta_{O2}/2$</td>
</tr>
<tr>
<td>$\delta_{O2}/2$</td>
<td>$\delta_{I2}/2$</td>
<td>$\delta_{O2}/2$</td>
<td>$\delta_{I2}/2$</td>
<td>$\delta_{O3}/2$</td>
</tr>
<tr>
<td>$\delta_{O3}/2$</td>
<td>$\delta_{I3}/2$</td>
<td>$\delta_{O3}/2$</td>
<td>$\delta_{I3}/2$</td>
<td>$\delta_{O4}/2$</td>
</tr>
</tbody>
</table>

#### Begining of SVM sector 1

- $V_{aN}$
- $V_{bN}$
- $V_{cN}$
- $V_{Nn}$
- $V_{an}$
- $V_{bn}$
- $V_{cn}$

**di/dt 1st measure**

**di/dt 2nd measure**
Position Signals for MC

- Matrix Converter state +1
- High Frequency Machine Model

\[ \frac{di_a}{dt} + 1 = \frac{U_{AB} - U_n}{l_a} = U_{AB} \cdot \frac{l_b + l_c}{l_a \cdot l_b + l_a \cdot l_c + l_b \cdot l_c} \]

\[ \frac{di_b}{dt} + 1 = - \frac{U_n}{l_b} = - U_{AB} \cdot \frac{l_c}{l_a \cdot l_b + l_a \cdot l_c + l_b \cdot l_c} \]

\[ \frac{di_c}{dt} + 1 = - \frac{U_n}{l_c} = - U_{AB} \cdot \frac{l_b}{l_a \cdot l_b + l_a \cdot l_c + l_b \cdot l_c} \]
Position Signals for MC

\[ \frac{di_a(+1)}{dt} = U_{AB} \cdot \frac{l_b + l_c}{l_a \cdot l_b + l_a \cdot l_c + l_b \cdot l_c} \]

\[ \frac{di_b(+1)}{dt} = -U_{AB} \cdot \frac{l_c}{l_a \cdot l_b + l_a \cdot l_c + l_b \cdot l_c} \]

\[ \frac{di_c(+1)}{dt} = -U_{AB} \cdot \frac{l_b}{l_a \cdot l_b + l_a \cdot l_c + l_b \cdot l_c} \]

\[ \frac{di_a(+1)}{dt} = \frac{U_{AB}}{g} \left( 2 - \frac{l_\Delta}{l_0} \cos(2 \cdot P \cdot \theta) \right) \]

\[ \frac{di_b(+1)}{dt} = -\frac{U_{AB}}{g} \left( 1 + \frac{l_\Delta}{l_0} \cos(2 \cdot P \cdot (\theta - \frac{4\pi}{3})) \right) \]

\[ \frac{di_c(+1)}{dt} = -\frac{U_{AB}}{g} \left( 1 + \frac{l_\Delta}{l_0} \cos(2 \cdot P \cdot (\theta - \frac{2\pi}{3})) \right) \]

\[ g = 3l_0 \left( 1 - \frac{l_\Delta^2}{4l_0^2} \right) \]

\[ \bar{p}_{PM} = p_a + e^{j2\pi/3} \cdot p_b + e^{j4\pi/3} \cdot p_c = p_a + jp_\beta = \]

\[ = \frac{2}{3} \frac{l_\Delta}{l_0} \left[ \cos(2P\theta) + e^{j2\pi/3} \cos(2P(\theta - \frac{2\pi}{3})) + e^{j4\pi/3} \cos(2P(\theta - \frac{4\pi}{3})) \right] \]

\[ p_a = -\frac{g}{U_{AB}} \frac{di_a(+1)}{dt} + 2 \]

\[ p_b = -\frac{g}{U_{AB}} \frac{di_c(+1)}{dt} - 1 \]

\[ p_c = -\frac{g}{U_{AB}} \frac{di_b(+1)}{dt} - 1 \]

- Position signals must be obtained for all 18 active states
Position Signals for MC

- From a/b/c to α/β

\[
p_a = -\frac{g}{U_{AB}} \frac{di_a}{dt} + 2
\]
\[
p_b = -\frac{g}{U_{AB}} \frac{di_c}{dt} - 1
\]
\[
p_c = -\frac{g}{U_{AB}} \frac{di_b}{dt} - 1
\]
Field Oriented Control scheme with angle estimation algorithm

PMSM

<table>
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<th>Parameters</th>
<th>Values</th>
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<tbody>
<tr>
<td>Rated power / Poles number</td>
<td>3.8kW / 6</td>
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<td>314.15rad/s / 12.2Nm</td>
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<td>0.5Ω / 4.35mH / 5.9mH / 0.73</td>
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Simulation results
Position Signals

- 30rpm (1% nominal speed) at full load (12.2Nm)
Simulation results

Speed reversal

- + 30rpm to -30 rpm (+/- 1% nominal speed) at full load (12.2Nm)
Sensorless Field Oriented Control scheme

**PMSM**

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Sensorless Simulation results
Speed reversal

- + 30rpm to -30 rpm (+/- 1% nominal speed) at full load (12.2Nm)
Sensorless Simulation results
Load Impact

- Full load (12.2Nm) impact at zero speed
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• Conclusions
Dynamic HF PMSM model

- Injecting a rotating HF voltage vector:
  \[
  \mathbf{v}_i = \begin{bmatrix} v_{\alpha i} \\ v_{\beta i} \end{bmatrix} = \hat{V}_i \begin{bmatrix} -\sin(\omega_i t) \\ \cos(\omega_i t) \end{bmatrix}
  \]

- The following HF current is obtained:
  \[
  \mathbf{i}_i = \begin{bmatrix} i_{\alpha i} \\ i_{\beta i} \end{bmatrix} = \begin{bmatrix} I_0 \cos(\omega_i t) + I_1 \cos(2\theta_r - \omega_i t) \\ I_0 \sin(\omega_i t) + I_1 \sin(2\theta_r - \omega_i t) \end{bmatrix}
  \]

- The amplitude of the negative sequence \( I_1 \) is proportional to the saliency \( \Delta L = (L_d - L_q)/2 \):
  \[
  I_0 = \frac{\hat{V}_i L}{L_d L_q \omega_i} ; \quad I_1 = \frac{\hat{V}_i \Delta L}{L_d L_q \omega_i}
  \]

- Frequency domain representation:
Homodyne Signal Processing

- Frequency domain
Homodyne Signal Processing

- Time domain

**Processing Steps**

- BPF
  \[ \tilde{i}_{\text{afli}} = \frac{\tilde{V}_i}{\omega_i L_\delta L_f} \left\{ L_{0s} + \Delta L_s e^{j(2\theta_s - \omega_0 t)} \right\} \]

- HPF
  \[ \tilde{i}_{\text{dqf}} = \frac{\tilde{V}_i \Delta L_s}{\omega_i L_\delta L_f} e^{j(2\theta_s - 2\omega_0 t)} \]

- \( e^{-j\omega_0 t} \)

- \( e^{j2\omega_0 t} \)

- atan/2

- \( \theta_e \)

**Processing Signals**

**Processing Signals Zoom**
Improving the position signals

- Harmonics exist on resolver signals
  - Non-sinusoidal distribution of saturation
  - Inverter effects – dead time & device voltage drop

Cleaning process
SMP Tables
Inverter effects

- Plot shows position signal in the time-domain with distortion during the zero-crossing of the fundamental line currents.

- Dead time and voltage drop must be compensated
Space Modulation Profiling (SMP) Table

Measured position signals at different loads

Load data into Matlab

Filter out ‘undesired’ signals

Obtain ‘clean’ position signals

Obtain ‘undesired’ signals (SMP Tables)
Harmonic Compensation using SMP

\[ \Delta I_{\beta} \rightarrow \Delta I_{\alpha} \]

\[ I_{\beta} \rightarrow I'_{\beta} \]

\[ I_{\alpha} \rightarrow I'_{\alpha} \]

\[ i_{sq}^* \rightarrow i_{sq} \rightarrow \Delta \theta \]

\[ \tan^{-1} \rightarrow 0.5 \rightarrow \hat{\theta}_\delta \rightarrow \hat{\theta}_r \]

\[ \text{Compensated Position Signals} \]

\[ \text{Sampled Alpha Position} \]

\[ \text{Sampled Beta Position} \]

\[ \text{Compensated Alpha Position} \]

\[ \text{Compensated Beta Position} \]
Experimental results

4kW SMPM machine Sensorless Position Control – 0% load

- Response to 180° position demand
Experimental results

4kW SMPM machine Sensorless Position Control – 100% load

- Response to 180° position demand
  - no integrator in control loop (incremental position only)
  - $i_{sq}$ (torque current) limited to 1.3 x rated
MC linearization. Dual Compensation

- General scheme

- Voltage Drop effect
MC linearization. Dual Compensation

- Four step commutation
- \((t_d1 + t_c + t_d2 = 1\mu s + 0.2\mu s + 0.5\mu s)\)

- Voltage Edge Uncertainty effect

\[ I_a > 0 \]
\[ V_A > V_B \]
**MC linearization. Dual Compensation**

- Model for Voltage Edge Uncertainty effect
- SVM

### SECTOR 1

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**Model for Voltage Edge Uncertainty effect**

- SVM

**SECTOR 1 Diagram**

![SECTOR 1 Diagram](image-url)
MC linearization. Dual Compensation

- Voltage Drop effect

- Voltage Edge Uncertainty effect

- Dual Compensation

input: phase current
output: compensating phase voltage
Sensorless Control with Matrix Converter

Experimental Set up

- Matrix Converter
  - 7.5kW
- Surface Mount Permanent Magnet Motor
  - 4kW
Sensorless Control with Matrix Converter

Dual Compensation in Matrix Converters

Voltage and current waveforms over time for different control techniques in matrix converters.
Sensorless Control with Matrix Converter

- Sensorless speed reversal at 30 RPM under no load.
  - Better speed response in the Matrix Converter.
  - Still some distortion due to cogging effect

**VSI + SMP +
dead time compensation**

**Matrix Converter + SMP +
dual compensation**

![Graph of VSI + SMP + dead time compensation](image1)

![Graph of Matrix Converter + SMP + dual compensation](image2)
Sensorless Control with Matrix Converter

- Sensorless speed reversal at 30 RPM under no load.
- Less angle error in the Matrix Converter

VSI + SMP +
dead time compensation

Matrix Converter + SMP +
dual compensation

Sensorless speed reversal at 30 RPM under no load.
Less angle error in the Matrix Converter
Sensorless Control with Matrix Converter

Sensorless control. Load impact

- 60 % Load impact at zero speed. Faster response in MC

VSI + SMP +
dead time compensation

Matrix Converter + SMP +
dual compensation
Conclusions

- **Aim for the Sensorless Control**
  - Volume and cost reduction & Increased reliability
- **Overview of Sensorless techniques**
  - Model Based
    - Fail at low/zero speed
  - Saliency based methods
    - Test pulse injection. Extra hardware
    - HF injection. Extra losses
- **Voltage Test Pulse Field Oriented Sensorless Control with Matrix Converters**
  - PWM Voltage Pattern modification. Medium voltage MC vectors are used as a pulse test
  - Angle Estimation Algorithm
  - Sensorless FOC Simulation results with SMPMSM. Position Signals, Speed Reversal and Load Impact
Conclusions

- HF injection Field Oriented Sensorless control has been presented.
  - 4 step homodyne demodulation.
  - Matrix Converters linearization is introduced. Dual compensation concept
  - Experimental results obtained in a off-the-shelf 4 kW SMPMSM and a 7.5kW Matrix Converter versus a standard VSI validate the usefulness of the presented techniques for:
    - Low and zero speed and
    - Load Impact at zero speed.

- Still research topic