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Reluctance Synchronous Machine Drives –
a Viable Alternative ?

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Overview

- Introduction
- History
- Modelling and steady state control
- Design
- Position sensorless control
- Manufacturing + Performance
- Cost
- Industry
- Assisted reluctance machines
- Conclusions: Answer to the question
Introduction

Reluctance machines

Non-salient induction

Single-salient reluctance

Double-salient “switched” reluctance

Single-salient flux barrier reluctance

→ Non-salient stator and unexcited rotor with magnetic asymmetry
'Reaktionsmaschine' (German) - 1960
'Unexcited synchronous machine' - 1930
'Polyphase reaction reluctance machine' - 1920
'Synchronous reluctance machine' (SRM or SyncRM)

Today

Rather

→ **Reluctance** synchronous machine (RSM)
  
  Wound-rotor synchronous machine
  
  Permanent magnet synchronous machine (PMSM)
Introduction

... a viable alternative?


• Kamper (2013).: "Reluctance synchronous machine drives – a viable alternative?," IEEE Joint IAS/PELS/IES Chapter Meeting, Graz (Austria).

Same title roughly 20 years later than Lipo and Vagati !!! Why don’t we see RSM drives?

Kostko said in 1923, "... it can hardly be expected that reaction motors will ever be extensively used."
History


History

Other: 1980’s


Conclusion 1: Direct on line / converter-fed

- IM with cage: VSD open loop
- RSM with / without cage: VSD open loop

With cage

With / without cage
\[ T = k \hat{\lambda}_s \hat{I}_s \sin \gamma \]
Modelling

Steady-state dq

\[ V_d = E_d + L_e I_{q1} \omega_r + I_{d1} R_s \]
\[ V_q = E_q + L_e I_{d1} \omega_r + I_{q1} R_s \]
Modelling

Torque

\[ T = \frac{3}{2} p \left( \lambda_d I_q - \lambda_q I_d \right) \]

→ If \( L_d = \frac{\lambda_d}{I_d} \) and \( L_q = \frac{\lambda_q}{I_q} \)

\[ T = \frac{3}{2} p \left( L_d - L_q \right) I_d I_q \]

\[ T = \frac{3}{4} p \left( L_d - L_q \right) \hat{I}_s^2 \sin(2\phi) \]
Modelling

Power factor

\[ P_f = \cos \left( \tan^{-1} \left( \frac{\frac{L_d}{L_q} \cdot \frac{I_d}{I_q} + \frac{I_q}{I_d}}{\frac{L_d}{L_q} - 1} \right) \right) \]
Modelling

Variation of dq Inductances

\[ T = \frac{3}{2} p (L_d - L_q) \hat{I}_s^2 \sin(2\phi) = k \Delta L(\phi) \sin(2\phi) \]
Modelling

\[ T = k \Delta L(\phi) \sin(2\phi) \]

\[ \frac{\partial \Delta L}{\partial \phi} = -\cot(2\phi) \Delta L(\phi) \]

\[ \Rightarrow 45^\circ < \phi < 90^\circ \]
Steady-state control

RSM drive

Closed loop current control with rotor position feedback
Steady-state control

Torque and Power factor

- Maximum Torque Locus
- $I_s I = 1.0 \text{ p.u.}$
- $I_s I = 0.7 \text{ p.u.}$
- $I_s I = 0.3 \text{ p.u.}$

Torque (Nm)

Current Space Phasor Angle (deg.)

Power Factor

Current Space Phasor Angle (deg.)
Steady-state control

Current control

\[ \phi_1 = 65^\circ \]
\[ \phi_2 = \phi_m \]
Steady-state control

Control block diagram
Steady-state control

Field weakening

- $\phi_m = 76^\circ$
- $\phi_m = 83^\circ$
- $\phi_m = 90^\circ$

Graph showing power vs. speed with different field weakening angles.
Use constant current angle in sub-base speed region for maximum T/Amp.

RSM drive has a poor constant power speed range (CPSR) and, hence, is not suited for applications that require a large CPSR.

Compares not as good to the IM drive in terms of the CPSR.
Design

Rotor type

Axially laminated Normal laminated with internal flux barriers

... due to manufacturing costs and possible rotor iron losses in axially laminated rotors
Design

Multi layer internal flux barriers

9 kW

42 kW

110 kW

42 kW
Design

FE design optimisation

Begin
Set initial values

\( r = 1 \)

Adjust initial values

Algorithm determines new vector directions

Minimise (maximise) \( Y \) along new vector directions

Is \( Y \) at an absolute minimum (maximum)?

No

Yes

End

\([X] = \) multidimensional vector containing machine variables

\([X] \)

\( Y \)

Call Finite Element Program

\( Y \) = output function value such as torque, efficiency etc.
Design

FE design optimisation

Maximum T/current

Maximum T/kVA
Design

Vagati – number of barriers and positions

\[ n_b = \text{number of barriers per pole pair} \]

\[ n_s = \text{number of slots per pole pair} \]

\[ n_b = n_s \pm 2, \pm 4, \ldots \]

In this case:

\[ \rightarrow 14 = 18 - 4 \]
An example using circular shaped flux barriers with certain widths for each flux barrier
Design

Shaping air/iron and iron webs

→ Shape iron segments rather
→ Rather no iron webs
Design

Asymmetric rotor

→ Reducing torque ripple without skewing

Sanada, Morimoto, 2004; Bianchi, 2006
Design

Mechanical strength

Von Mises Stress Distribution due to 4500 rpm Rotation on Deformed Model (Blown-up)
Design

Chording

9 kW

42 kW

Torque (p.u.)

Chording

Finite element

Proportional to $k_w^2$

N = 36

N = 48
Design

Skew

9 kW

42 kW
Design

2-pole design

2-pole  4-pole  6-pole
Position sensorless control

Methods

- Standstill to low speeds (saliency based)
  - Rotating HF injection  →  Impuls voltage vector
  - Alternating HF injection  →  PWM without injection
  - Arbitrary injection (parameter insensitive)
- Minimum to rated speeds (fundamental model based)
  - Fundamental saliency method (RSM)
  - Active flux method (Generic)
- Hybrid method (with hysterises band)

W.T. Villet, M.J. Kamper, P. Landsmann and R. Kennel, "Hybrid sensorless speed control of a reluctance synchronous machine through the entire speed range", 15th International Power Electronics and Motion Control Conference and Exposition (EPE-PEMC 2012: ECCE Europe), Novi Sad (Serbia), 4-6 Sept. 2012
Position sensorless control  Alternating injection
Position sensorless control  Alternating injection

\[
i^{r}_{sq(\text{demodulated})} \approx \frac{u_c L_\Delta \theta_\Delta}{L_d L_q \omega_c}
\]

Saliency → \( L_\Delta = \frac{L_d - L_q}{2} \); Position error → \( \theta_\Delta = \theta_e - \hat{\theta}_e \)

\[
L_d = \frac{\partial \psi_d}{\partial i_d}; \quad L_q = \frac{\partial \psi_q}{\partial i_q}
\]

→ Saliency is load dependent
Position sensorless control  Shift and coefficient

Frenzke, EPE (Dresden) 2005

Magnetic axis shift (real position error)

\[
\theta_{\Delta 0} = -\frac{1}{2} \tan^{-1} \left( \frac{2L_{dq}}{L_d - L_q} \right)
\]

with

\[
L_{dq} = \frac{\partial \psi_d}{\partial i_q}
\]

Saliency coefficient – a measure for valuing the suitability of a motor for sensorless control (range of 0 – 1)

\[
\zeta = \sqrt{\left( L_d - L_q \right)^2 + 4L_{dq}^2}
\]

\[
\frac{L_d + L_q}{L_d + L_q}
\]
P. Landsmann, R. Kennel, H.W. de Kock and M.J.Kamper, "Fundamental saliency based encoderless control for reluctance synchronous machines", XIX International Conference on Electrical Machines (ICEM), Rome (Italy), Sep 2010
Position sensorless control

Performance of sensorless control (based on 1.5 kW RSM tests):

- Almost no effect on efficiency and thermal.
- No higher audible noise with sensorless FOC.
- Rotor skewing is no problem with sensorless control.
- Rated standstill torque could be obtained sensorless.
- Sensorless with low to zero load current? → need alternative rotor design and manufacturing.

Manufacturing + Performance

2.8 kW DC
2.2 kW IM
9 kW RSM

9 kW @ 1500 r/min RSM rotor - skewed

9 kW RSM
5.5 kW standard line started Induction Machine – stator and casing

9 kW Converter-fed RSM – stator in 5.5 kW IM casing
Manufacturing

42 kW RSM
Manufacturing

Loher 30 kW RSM
Performance tests

Abbildung 2 Prüfstand im IM Prüffeld zur Messung des RSM

<table>
<thead>
<tr>
<th></th>
<th>Airgap</th>
<th>Current</th>
<th>Voltage</th>
<th>Pout</th>
<th>Efficiency</th>
<th>Tempr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>IM</td>
<td>0.7 mm</td>
<td>55.4 A</td>
<td>400 V</td>
<td>30 kW</td>
<td>91.7</td>
<td>59 K</td>
</tr>
<tr>
<td>RSM</td>
<td>0.6 mm</td>
<td>52.5 A</td>
<td>457 V</td>
<td>28.3 kW</td>
<td>93.8</td>
<td>45 K</td>
</tr>
</tbody>
</table>
Manufacturing

110 kW RSM
Locally manufactured 110 kW RSM Rotor
Performance tests

110 kW RSM

![Graph showing Speed (r/min) vs. Torque (Nm) with line graphs for IM and RSM.](image)
• Cost of RSM rotor versus IM rotor
• Energy (kJ or kWh) required to manufacture the rotor
• RSM rotor → Punch of laminations and End plates
• Epoxy casted RSM rotor ?
• Cost of the RSM inverter versus IM inverter ?
Traditional induction motor

Losses

High output SynRM motor
### Pump application example

<table>
<thead>
<tr>
<th></th>
<th>High output SynRM motor</th>
<th>ABB IE2 induction motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame size</td>
<td>160, 174 kg</td>
<td>180, 222 kg</td>
</tr>
<tr>
<td>Motor efficiency</td>
<td>DOL: N/A, VSD: 92.8%</td>
<td>DOL: 92.4%, VSD: ~91.0%</td>
</tr>
</tbody>
</table>

Customer benefit: Same output from a smaller size or higher output from the same size

### Fan application example

<table>
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<tr>
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<th>High output SynRM motor</th>
<th>ABB IE2 induction motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame size</td>
<td>160, 157 kg</td>
<td>200, 298 kg</td>
</tr>
<tr>
<td>Motor efficiency</td>
<td>DOL: N/A, VSD: 93.7 %</td>
<td>DOL: 93.4%, VSD: ~92.2%</td>
</tr>
</tbody>
</table>

Customer benefit: Reduced system space
- lower weight, easier installation

![Image of motors]
For small motors at 3 or 4 kW level, as much as 60 percent more power can be obtained for the same temperature rise.

Since there is always a frequency converter between the motor and the grid, the lower power factor is not apparent on the grid side and consequently does not have an impact on the grid supply dimensioning. However, the lower power factor may sometimes mean that a frequency converter with a higher current rating is needed.
RSM / IM working

Electric and magnetic circuits

deficit in q-axis circuits explain the differences between the machines
Some other questions

→ Audible noise of RSM drives?
  … this seems not to be an issue.

→ Bearing currents in converter-fed RSMs?
  … are bearing currents worse than e.g. in the IM drive?
Assisted RSMs

RSM

A-RSM

FI-IPM

C-RSM

IPM

Bi-axial

(a)

(c)

(e)

(b)

(d)

(f)
Assisted RSMs

IPM

IM stator

Epoxy bonded rare-earth layer
Comparison

RSM, IM, PM-RSM

Graphs showing comparison of current, power factor, and torque for RSM, IM, and PM-RSM at different speeds.
Assisted RSMs

Wound rotor

Assisted RSMs

Field intensified

RSM
FI-IPM
FI-IPM

p.u. stack volume for the same power

\[ \rightarrow 1.0 \]
\[ 1.0 \]
\[ 0.8 \]

Two main reasons why RSM-drives did not become viable alternative VSDs the past 20 years:

- Efficiency was less of an issue.
- A shaft position sensor was necessary.

These have changed now:

- Efficiency of VSDs today is extremely important and RSM drives have that advantage.
- RSM position sensorless control is viable for certain small and medium power VSD applications.
Conclusions

Viability of RSM drive

• ABB:
  → 17 – 350 kW RSM drives in production for pump and fan applications.

• KSB (Frankenthal, Germany):
  → 0.55 – 45 kW for pumps

• Siemens?
  → ABB and KSB are in mass production, although for limited number of applications (pumps, fans).
Conclusions

Other applications

• Multi-gear EV drives


• RSG high speed windgenerators ?
Thank You for Your Attention
Vielen Dank für Ihre Aufmerksamkeit

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