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Reluctance Synchronous Machine Drives – a Viable Alternative ?

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Overview

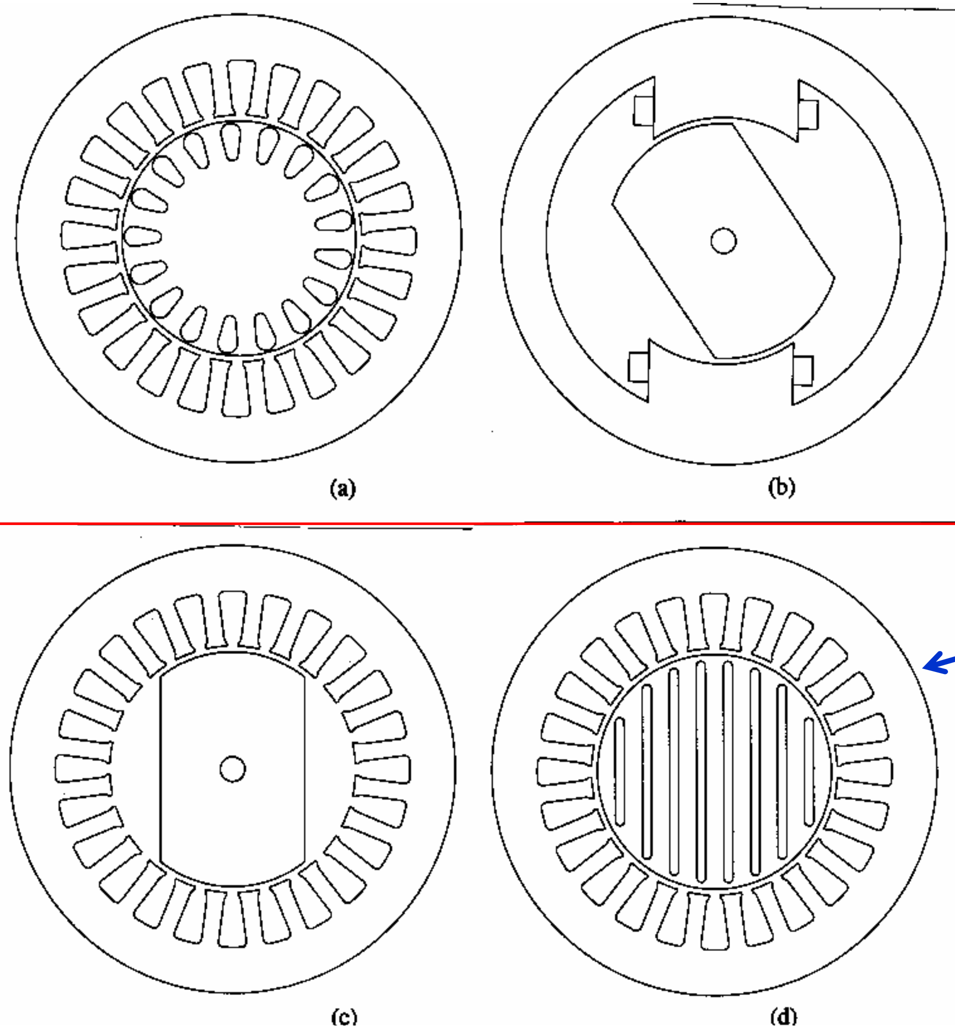
- Introduction
- History
- Modelling and steady state control
- Design
- Position sensorless control
- Manufacturing + Performance
- Cost
- Industry
- Assisted reluctance machines
- Conclusions: Answer to the question

Introduction

Reluctance machines

Non-salient induction

Double-salient "switched" reluctance



Single-salient reluctance

focus

Single-salient flux barrier reluctance

→ Non-salient stator and unexcited rotor with magnetic asymmetry

Introduction

Name:

'*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

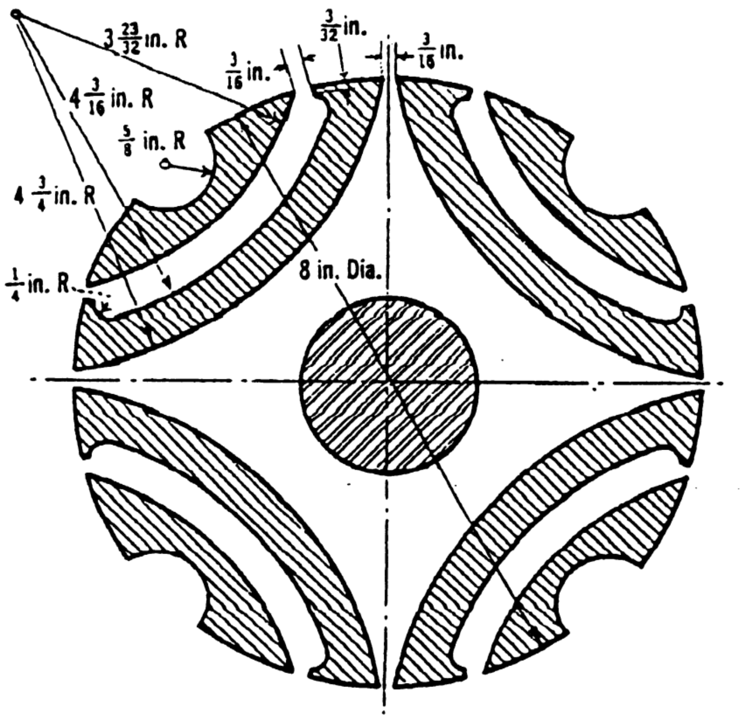
- Lipo(1991) T.A.: "Synchronous reluctance machines – a viable alternative for AC drives," Electr Mach Power Syst, vol. 19, pp. 659-671.
- Vagati (1994) A.: "The synchronous reluctance solution: a new alternative in A.C. drives," Proc IEEE IECON (Bologna), vol. 1, pp. 1-13.
- Kamper (2013).: "Reluctance 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?

History

Kostko

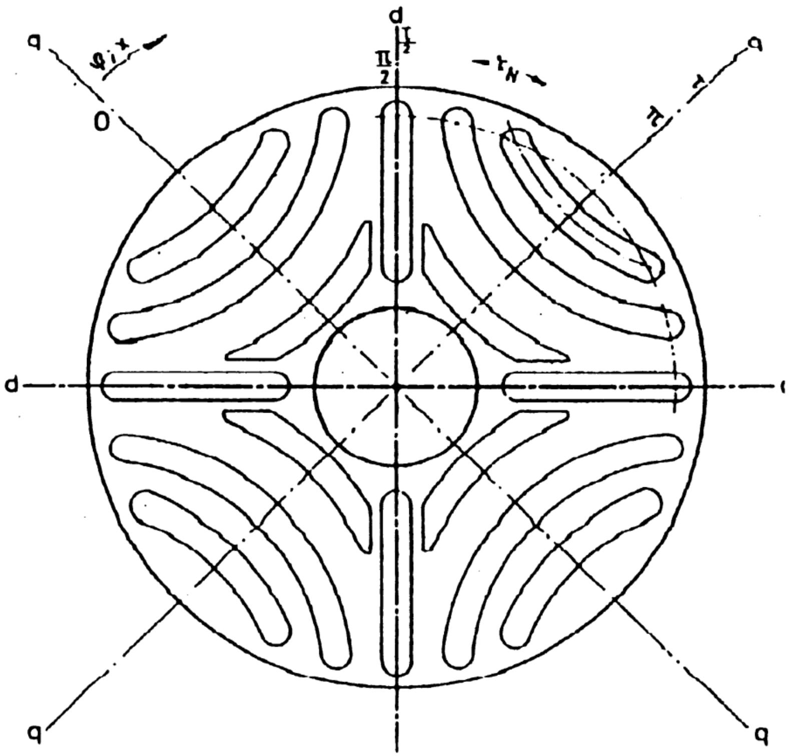
Kostko (1923) J.K.: "Polyphase reaction synchronous motors", Journal AIEE, vol. 42, pp. 1162-1168.



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

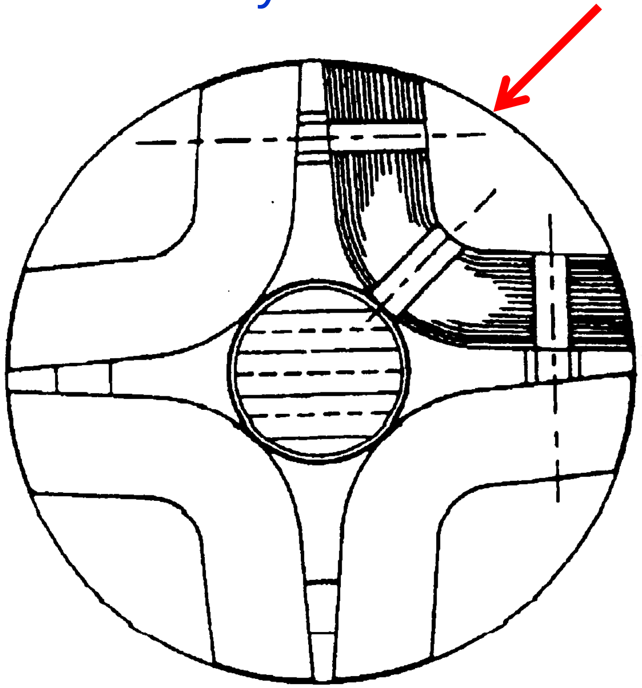
History

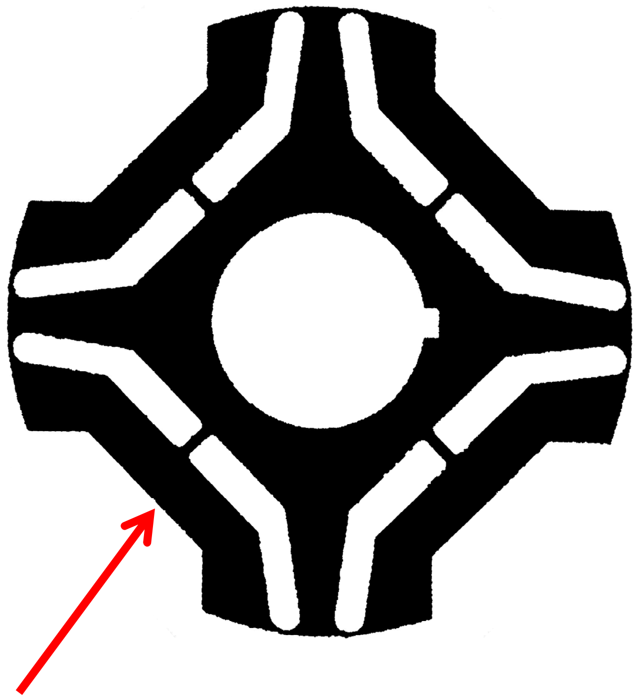
Brinkman (1965) J.: "Theoretische und experimentelle untersuchen an einem motor mit verbesserter ausnuzung des reaktionsprinzips", Dissertation, Fakultät für Maschinenwesen der Technischen Hochshule Carolo-Wilhelmina, Braunschweig, Jan 1965.



History

Cruickshank (1971) A.J.O. *et al*: "Theory and performance of reluctance motors with axially laminated anisotropic rotors", Proc. IEE, vol 118, no. 7.





Honsinger (1971) V.B.: "The inductances L_d and L_q of reluctance machines", IEEE Trans. PAS, vol 90, no. 1.

History

Other: 1960's and 70's

Lipo (1967) T.A. and Krause, P.C.: "Stability analysis of a reluctance-synchronous machine", IEEE Trans. PAS, vol 86, no. 7, pp. 825-834.

Krause (1969), P.C. and Lipo T.A.: "Analysis and simplified representations of rectifier-inverter reluctance-synchronous motor drives", IEEE Trans. PAS, vol 88, no. 6, pp. 825-834.

Ong (1977), C.M. and Lipo T.A.: "Steady state analysis of a current source inverter reluctance motor drive", IEEE Trans. PAS, vol 96, no. 4.

Faucher (1979), J. *et al*: "Characterization of a closed-loop current-fed reluctance machine taking into account saturation", IEEE Trans. on Industrial Applications, vol 15, no. 5, pp. 482-488.

History

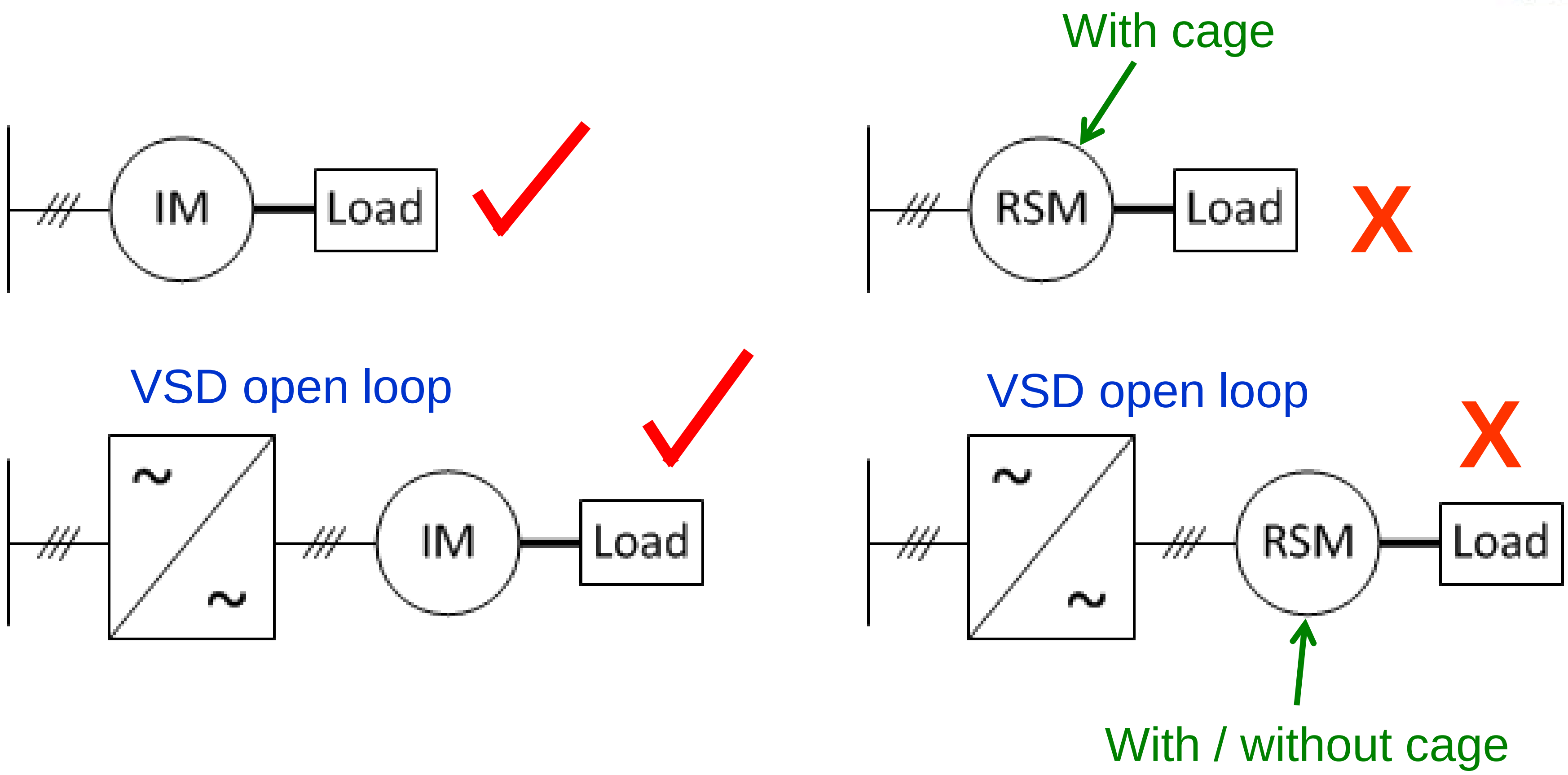
Al-Antably (1985) A. and Hudson T.L.: "The design and steady state performance of a high efficiency reluctance motor", IEEE-IAS Annual Meeting, pp. 770-776.

Weh (1985) H. and Schroder U.: "Static inverter concepts for multiphase machines with square-wave current-field distributions", European Power Electronic (EPE) Conference (Brussels), pp. 1147-1152.

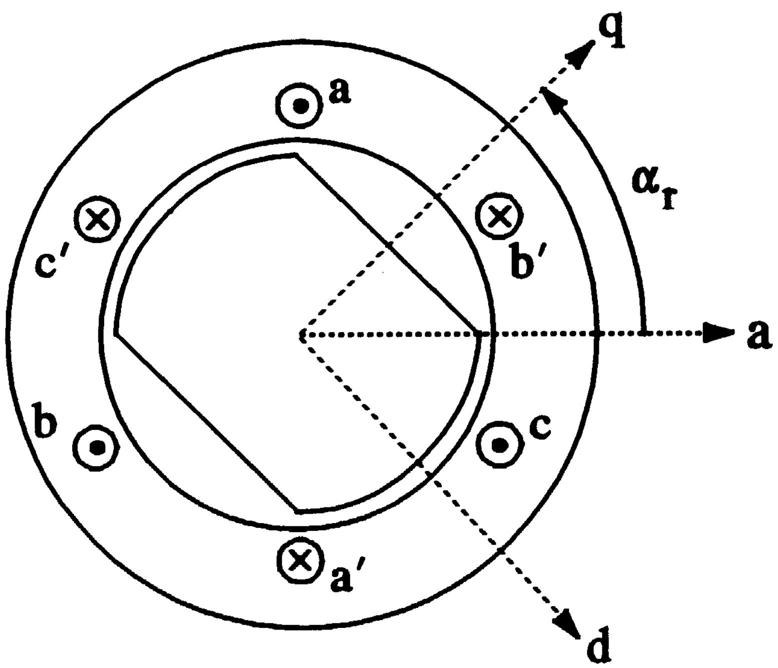
Fratta (1987) A., Vagati A. and Vilatta A.: "A reluctance motor drive for high dynamic performance applications", IEEE-IAS Annual Meeting, pp. 295-302.

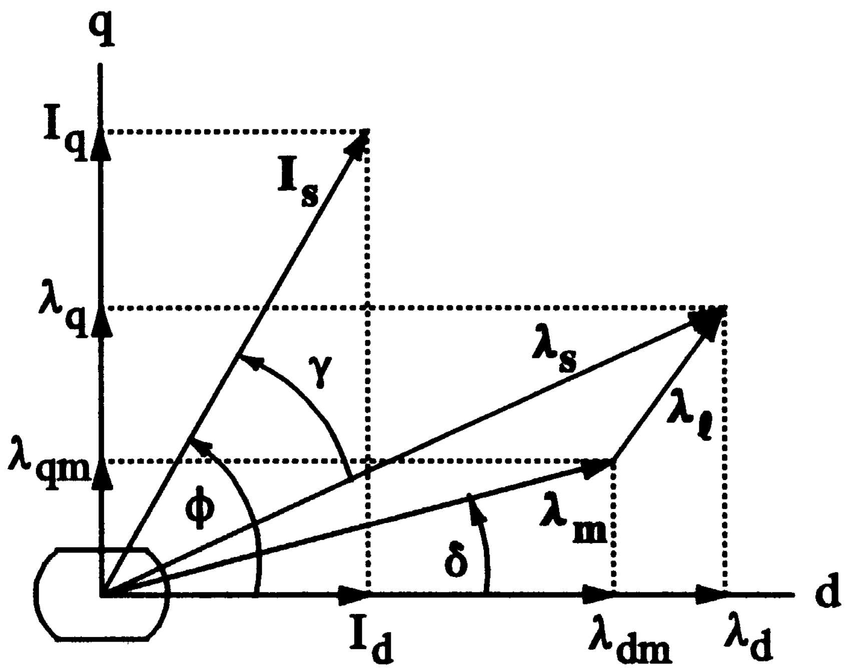
Conclusion 1

direct on line / converter-fed



$$T = k\hat{\lambda}_s \hat{I}_s \sin\gamma$$

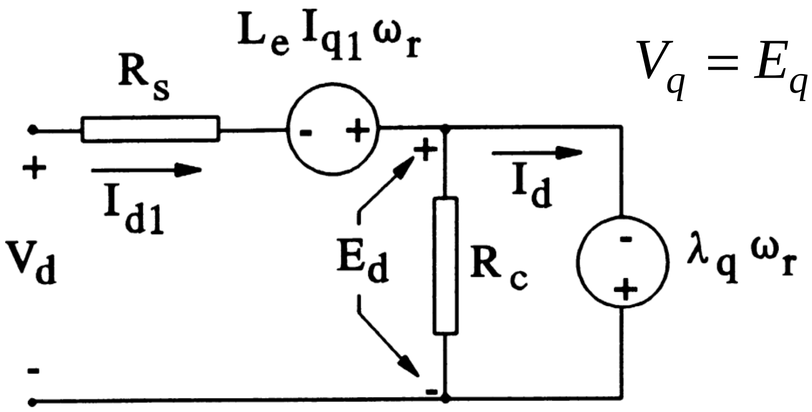


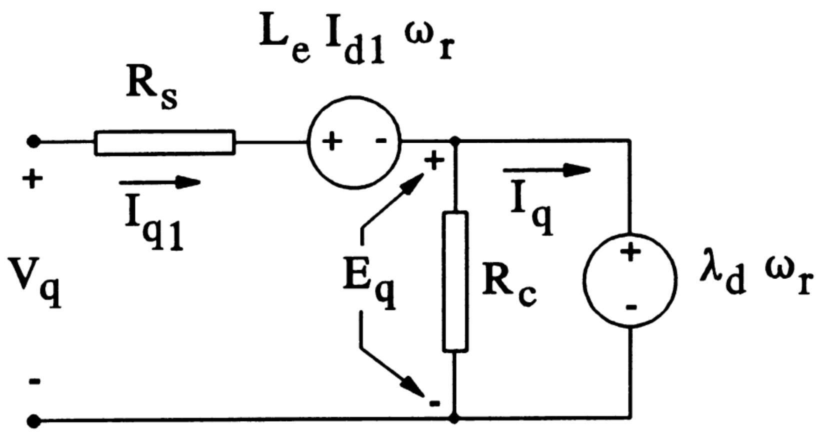


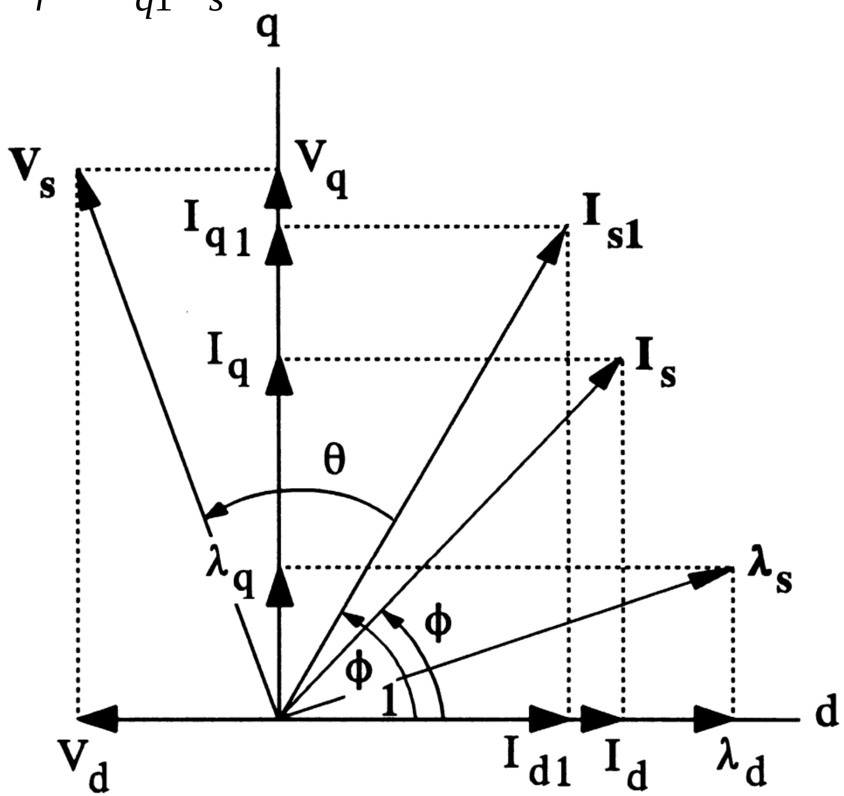
Modelling

$$V_d = E_d + L_e I_{q1}\omega_r + I_{d1}R_s$$

$$V_q = E_q + L_e I_{d1}\omega_r + I_{q1}R_s$$







Modelling

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

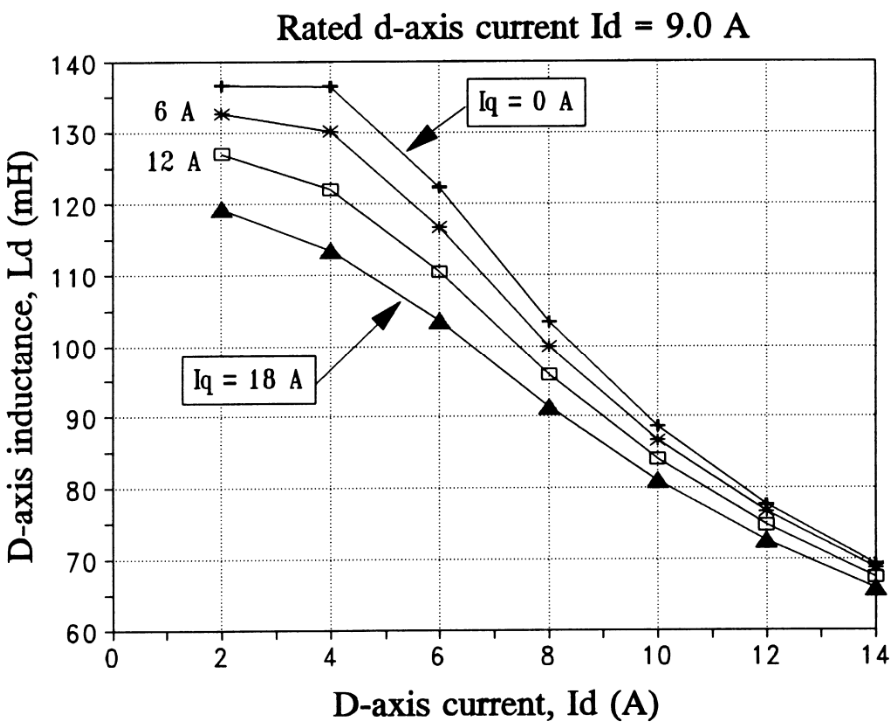
$$\rightarrow \text{If} \quad L_d = \frac{\lambda_d}{I_d} \quad \text{and} \quad L_q = \frac{\lambda_q}{I_q}$$

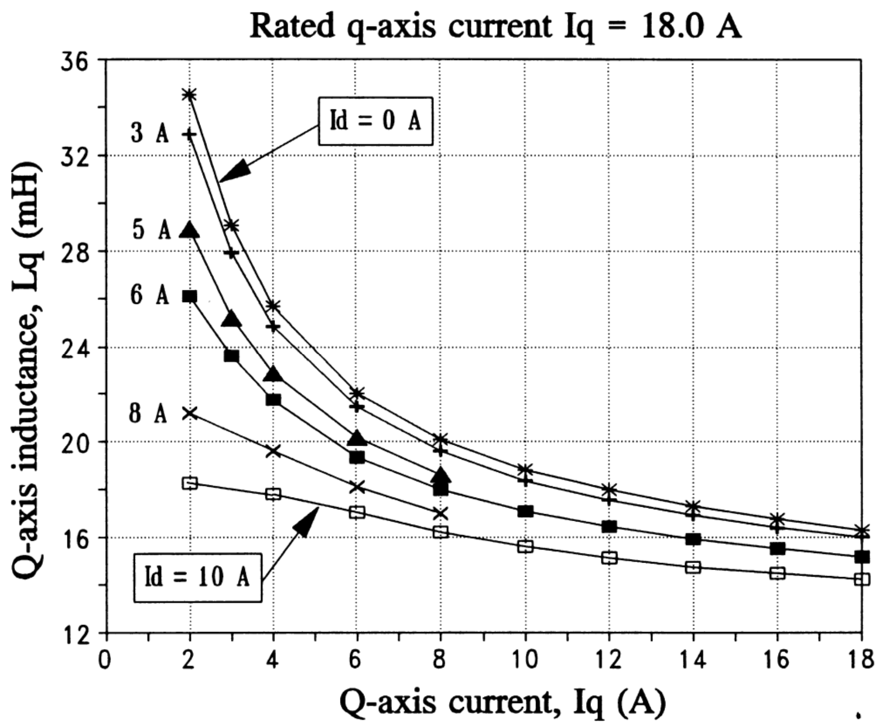
$$T = \frac{3}{2} p\left(L_d - L_q\right) I_d I_q$$

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

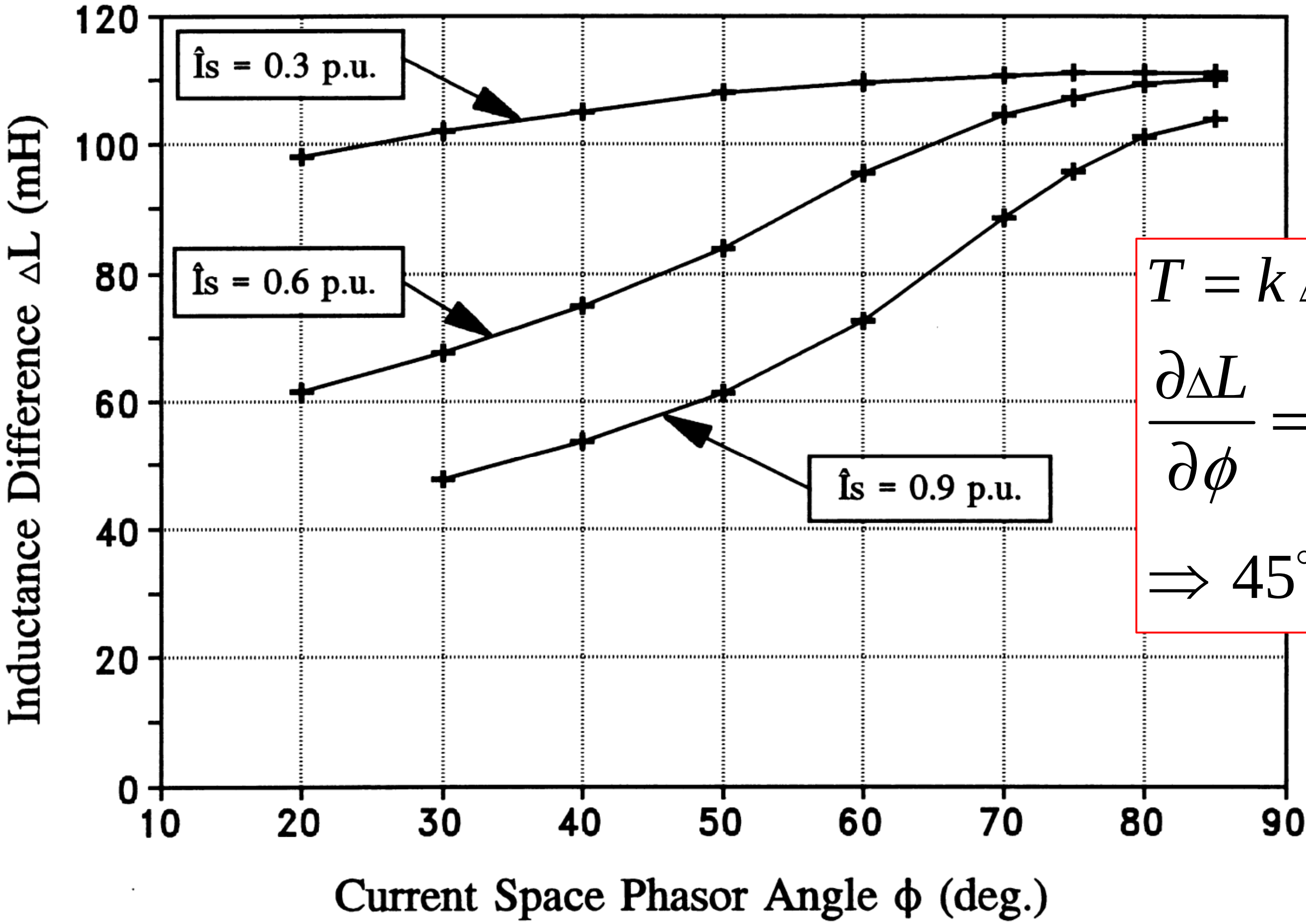
$$P_f = \cos\left(\tan^{-1}\left(\frac{\frac{L_d}{L_q}.\frac{I_d}{I_q} + \frac{I_q}{I_d}}{\frac{L_d}{L_q} - 1} \right) \right)$$

Variation of dq Inductances





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

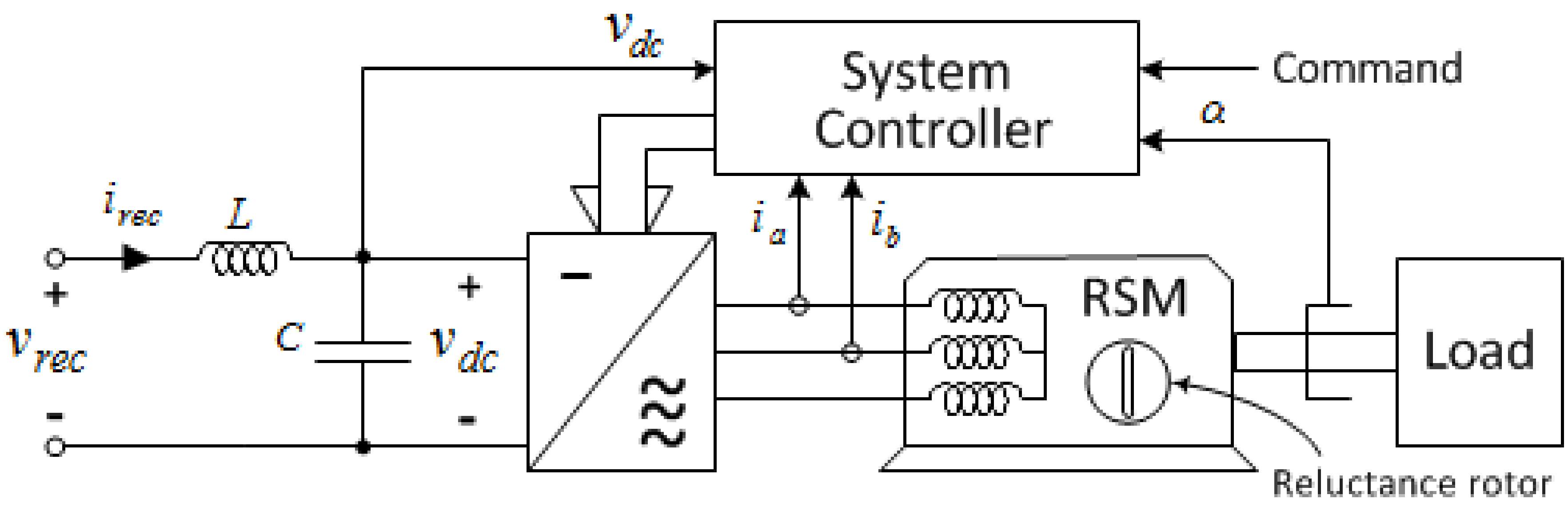


$$T = k\,\Delta L(\phi)\sin(2\phi)$$

$$\frac{\partial \Delta L}{\partial \phi} = -\cot(2\phi)\,\Delta L(\phi)$$

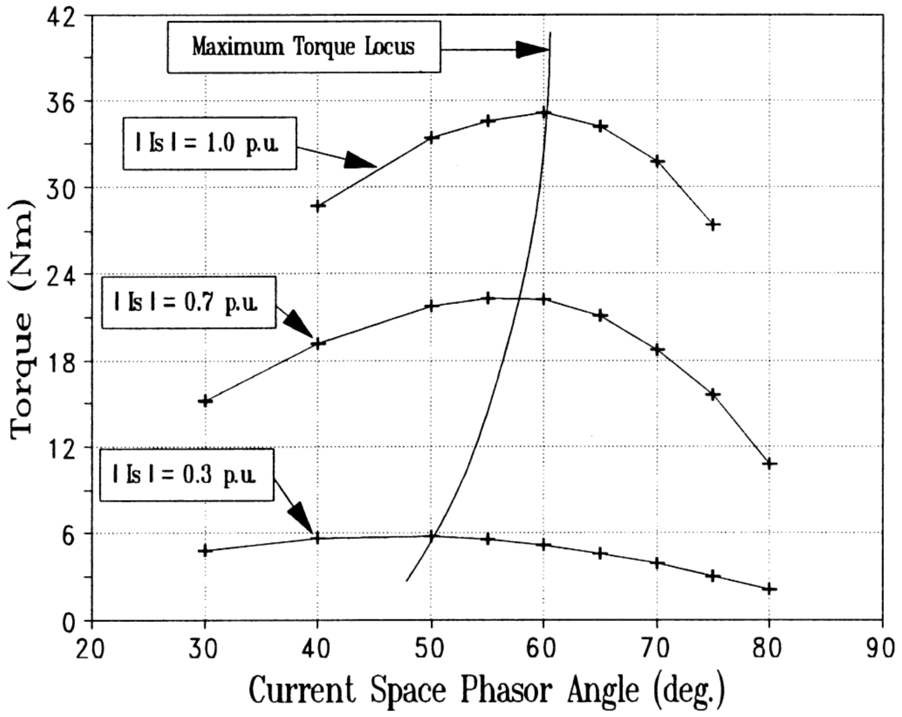
$$\Rightarrow 45^\circ < \phi < 90^\circ$$

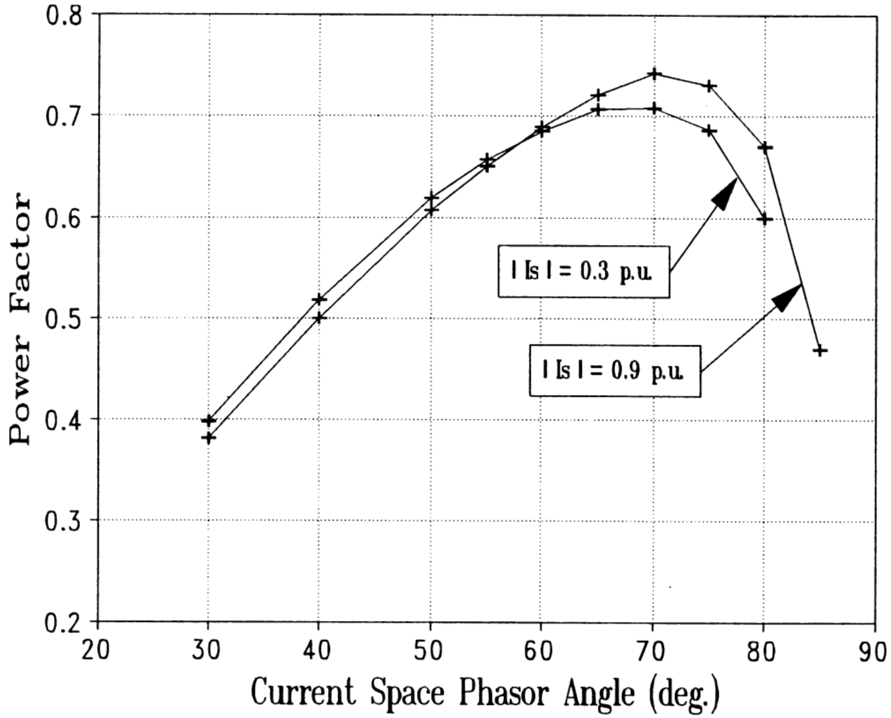
Steady-state control



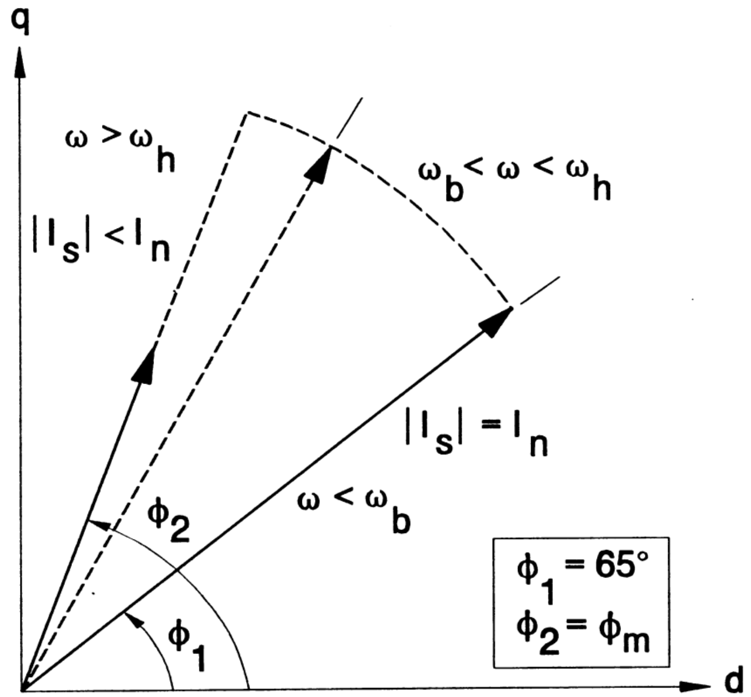
Closed loop current control
with rotor position feedback

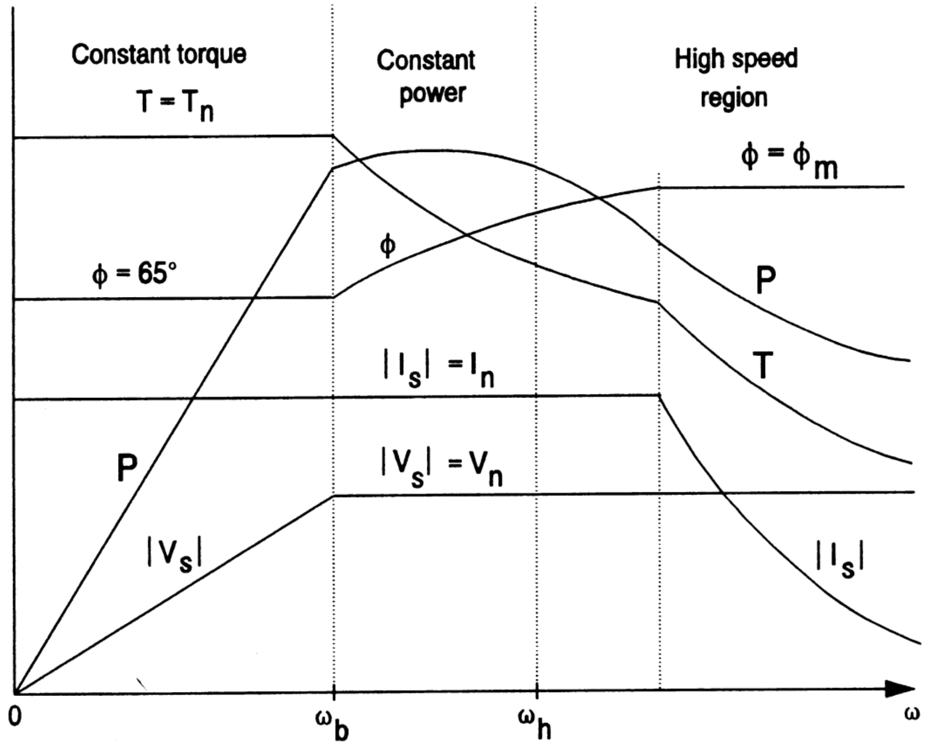
Steady-state control Torque and Power factor





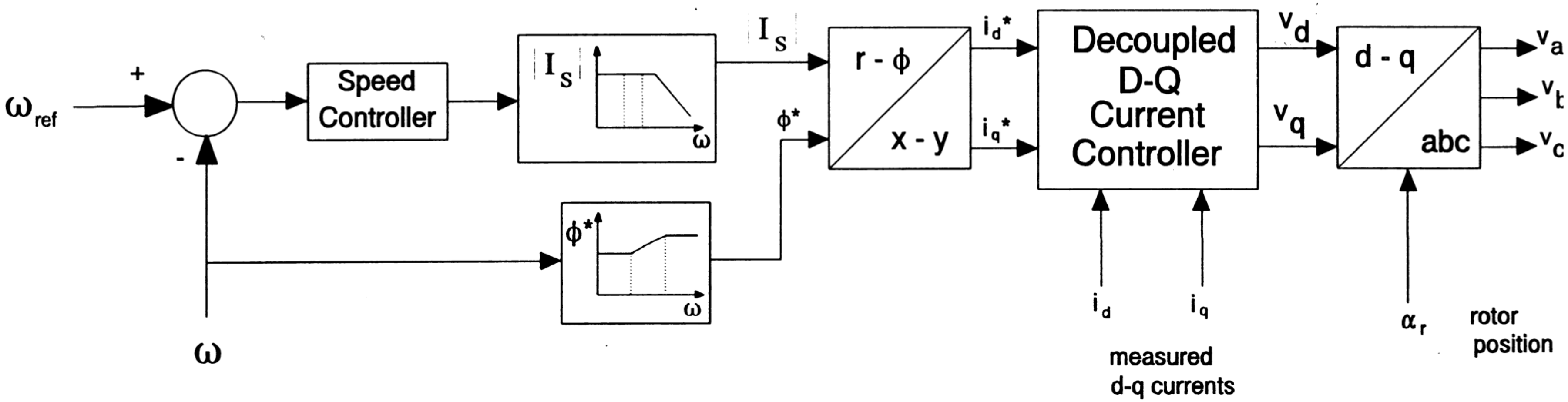
Steady-state control





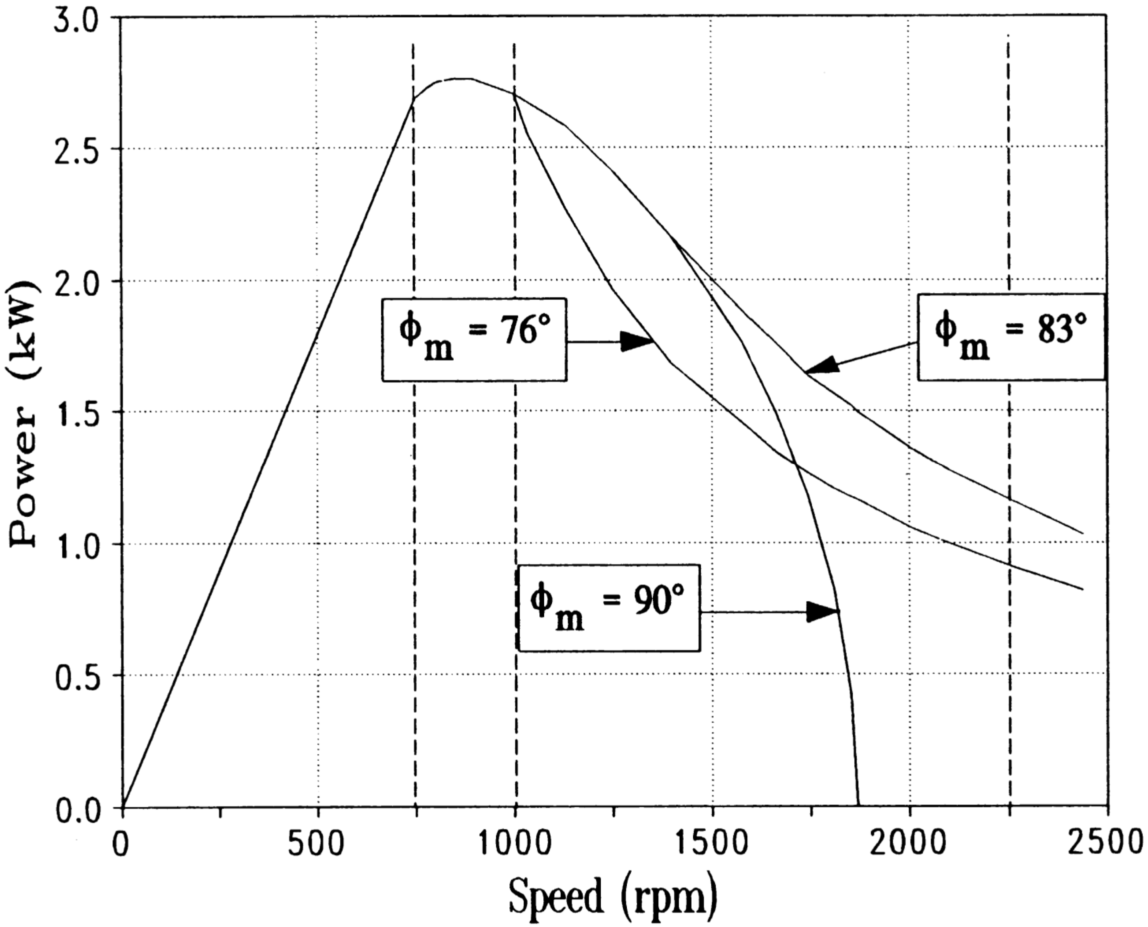
Steady-state control

Control block diagram



Steady-state control

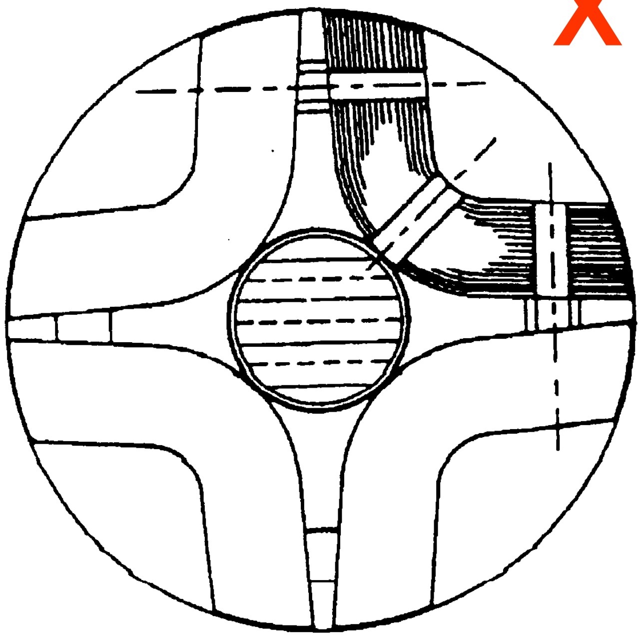
Field weakening

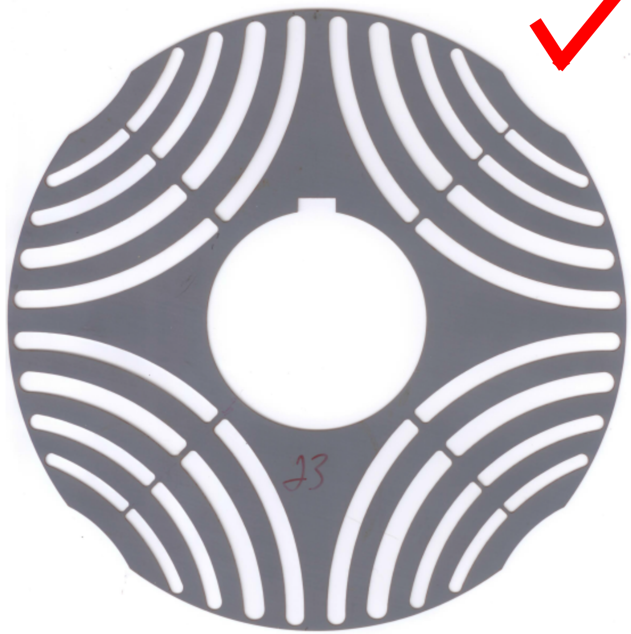


Conclusion 2

- → 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 requires a large CPSR
- → Compares not as good to the IM drive in terms of the CPSR

Design





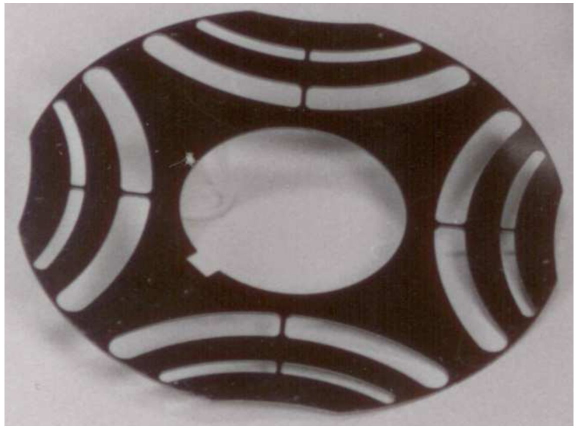
Axially laminated → **Normal laminated with internal flux barriers**

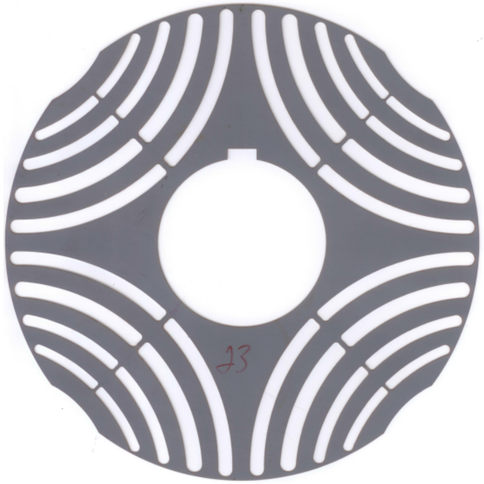
X … **due to manufacturing costs and possible rotor iron losses in axially laminated rotors**

Design

Multi layer internal flux barriers

9 kW





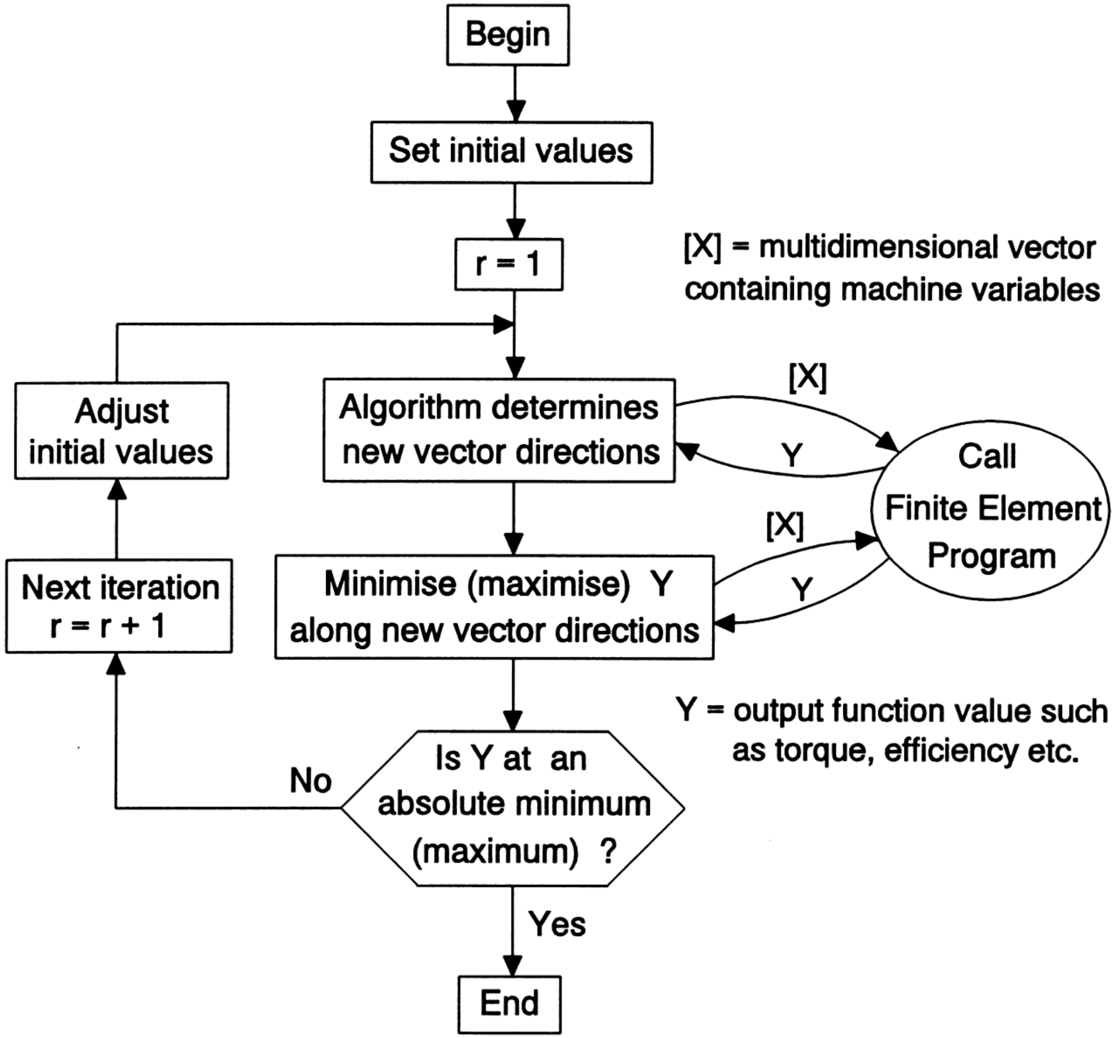
42 kW

110 kW

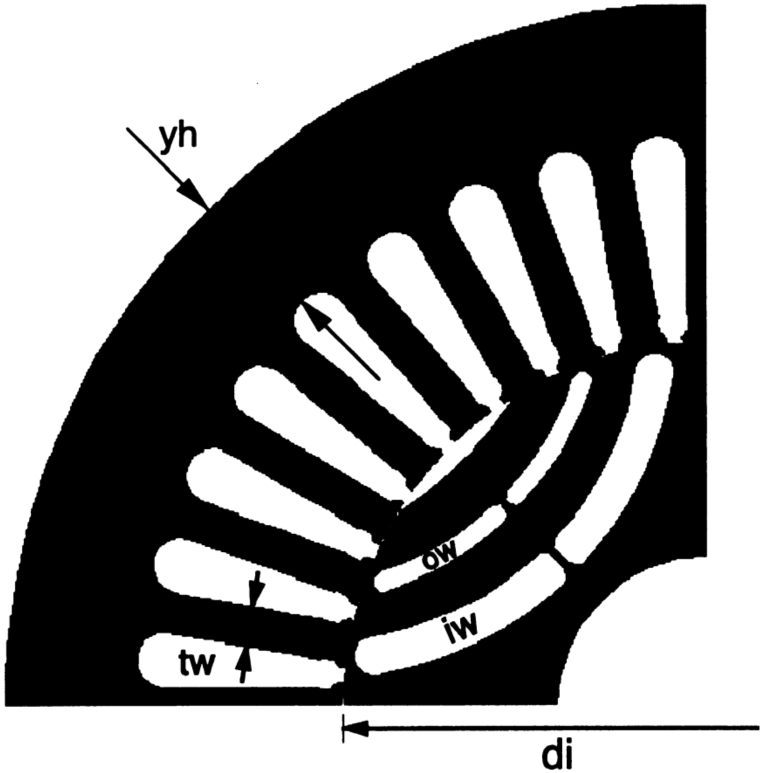
42 kW

Design

FE design optimisation



Design

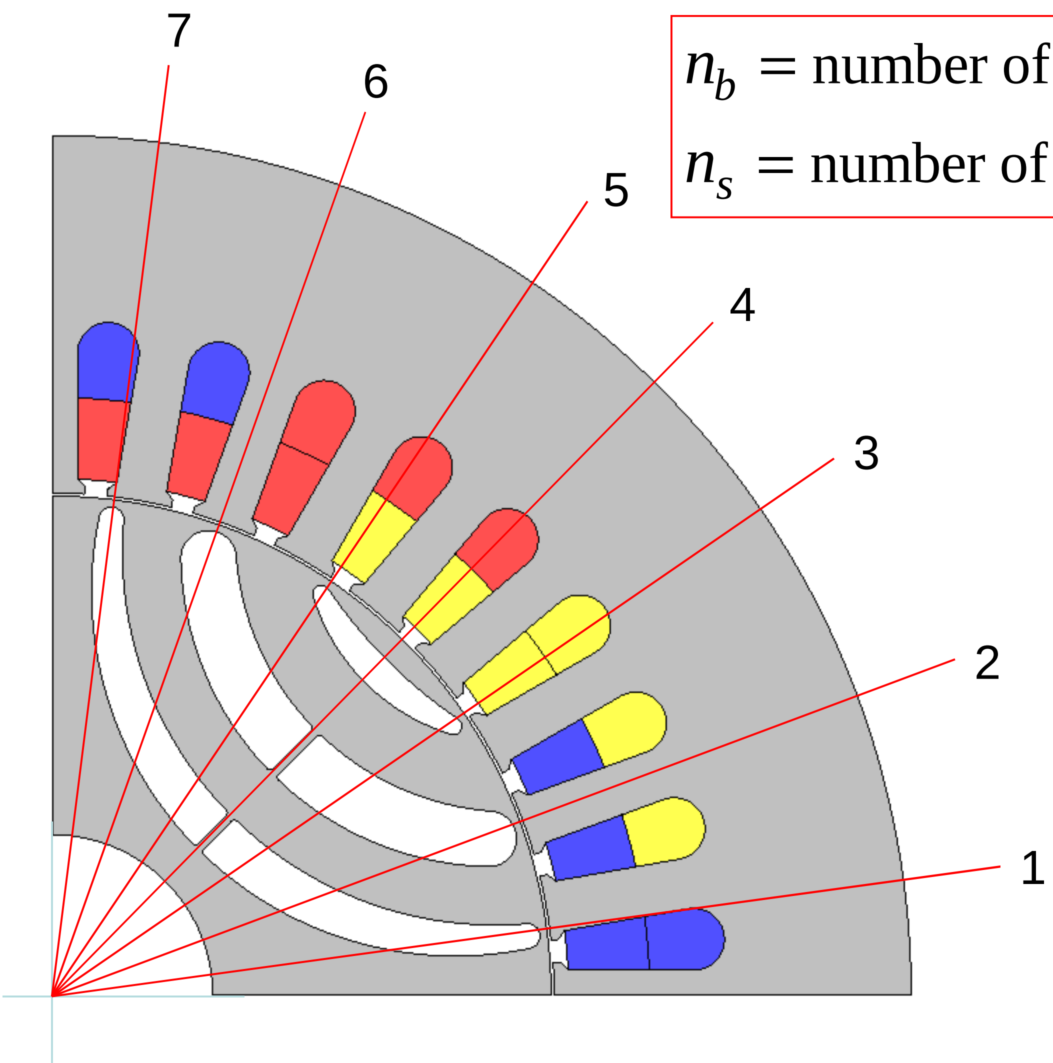


Maximum T/current

Maximum T/kVA

Design

Vagati – number of barriers and positions



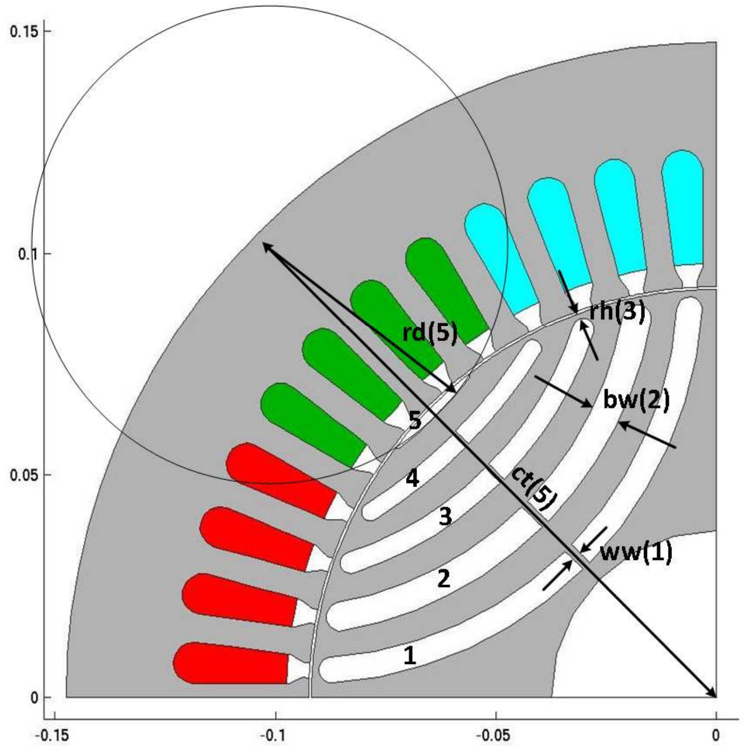
n_b = number of barriers per pole pair

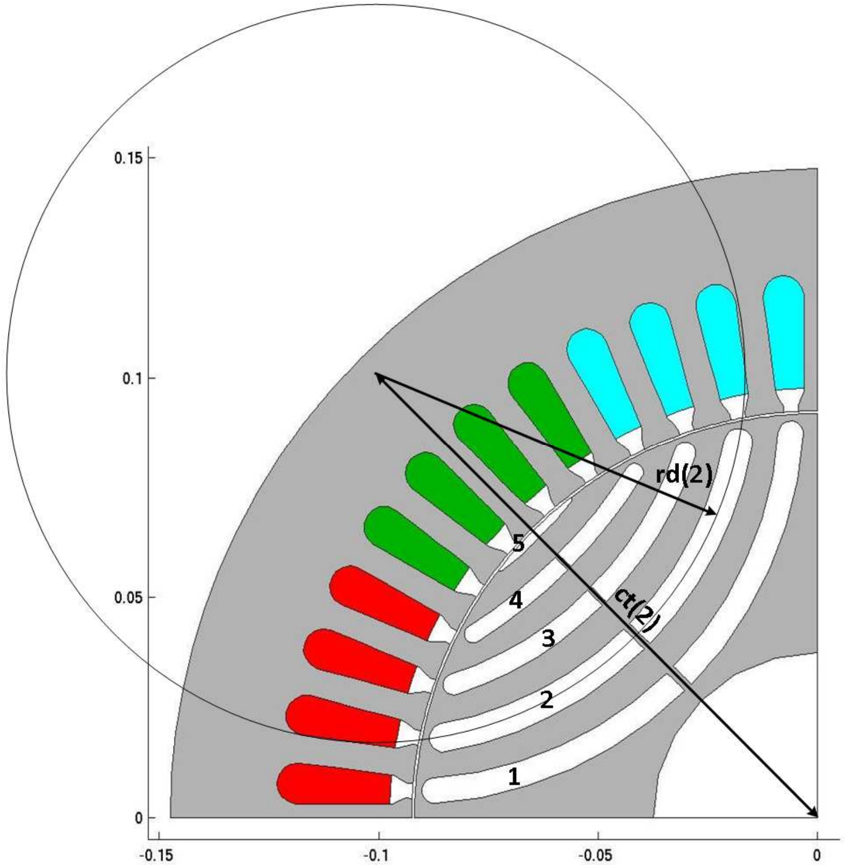
n_s = number of slots per pole pair

$$n_b = n_s \pm 2, \pm 4, \ldots$$

In this case:

$$\rightarrow 14 = 18 - 4$$

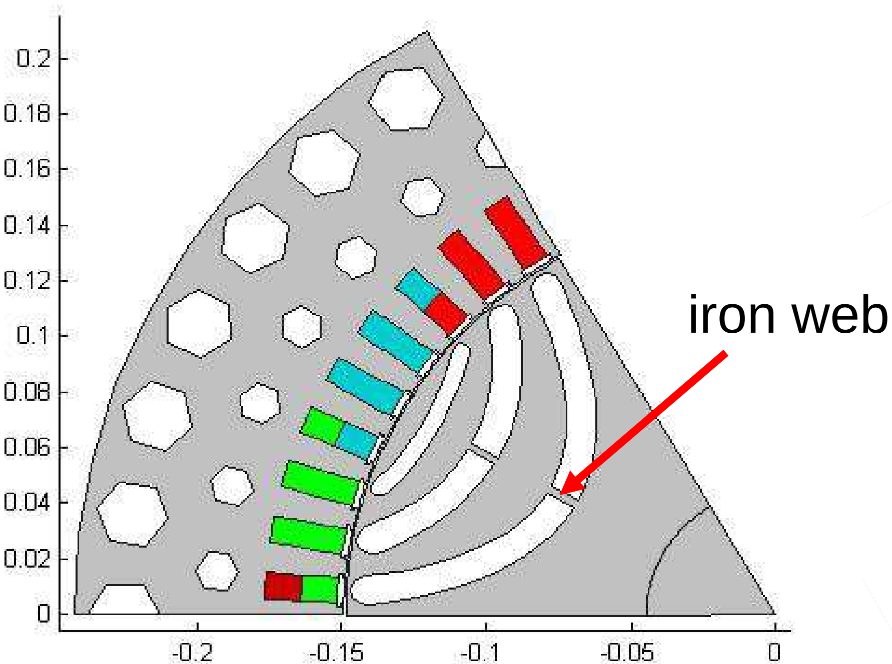




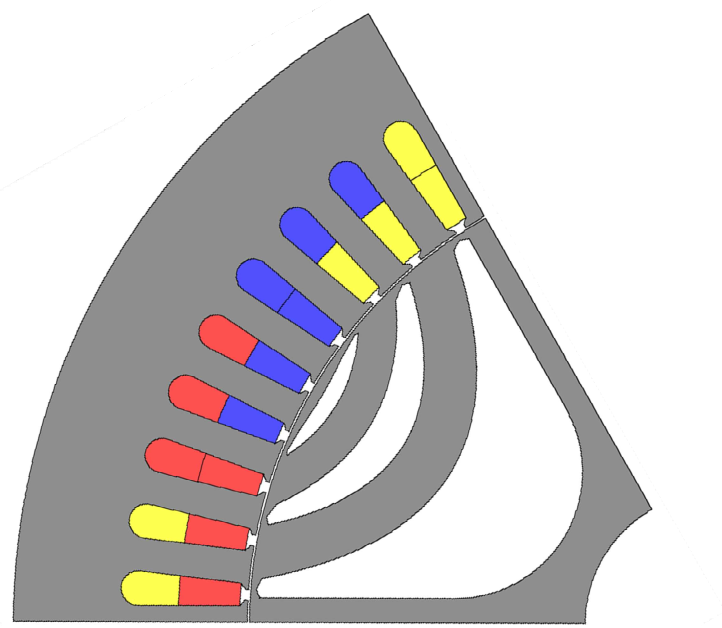
An example using circular shaped flux barriers with certain widths for each flux barrier

Design

Shaping air/iron and iron webs



110 kW

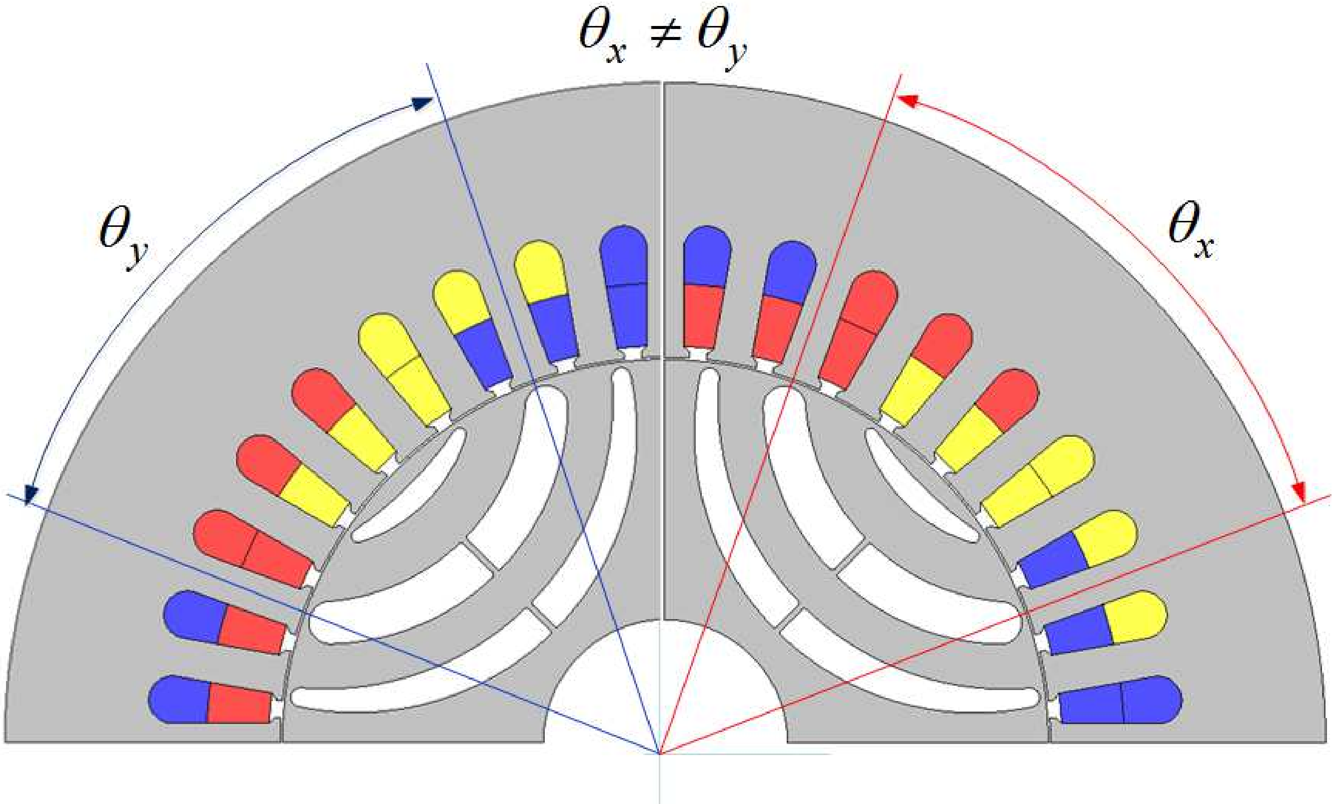


30 kW

→ Shape iron segments rather

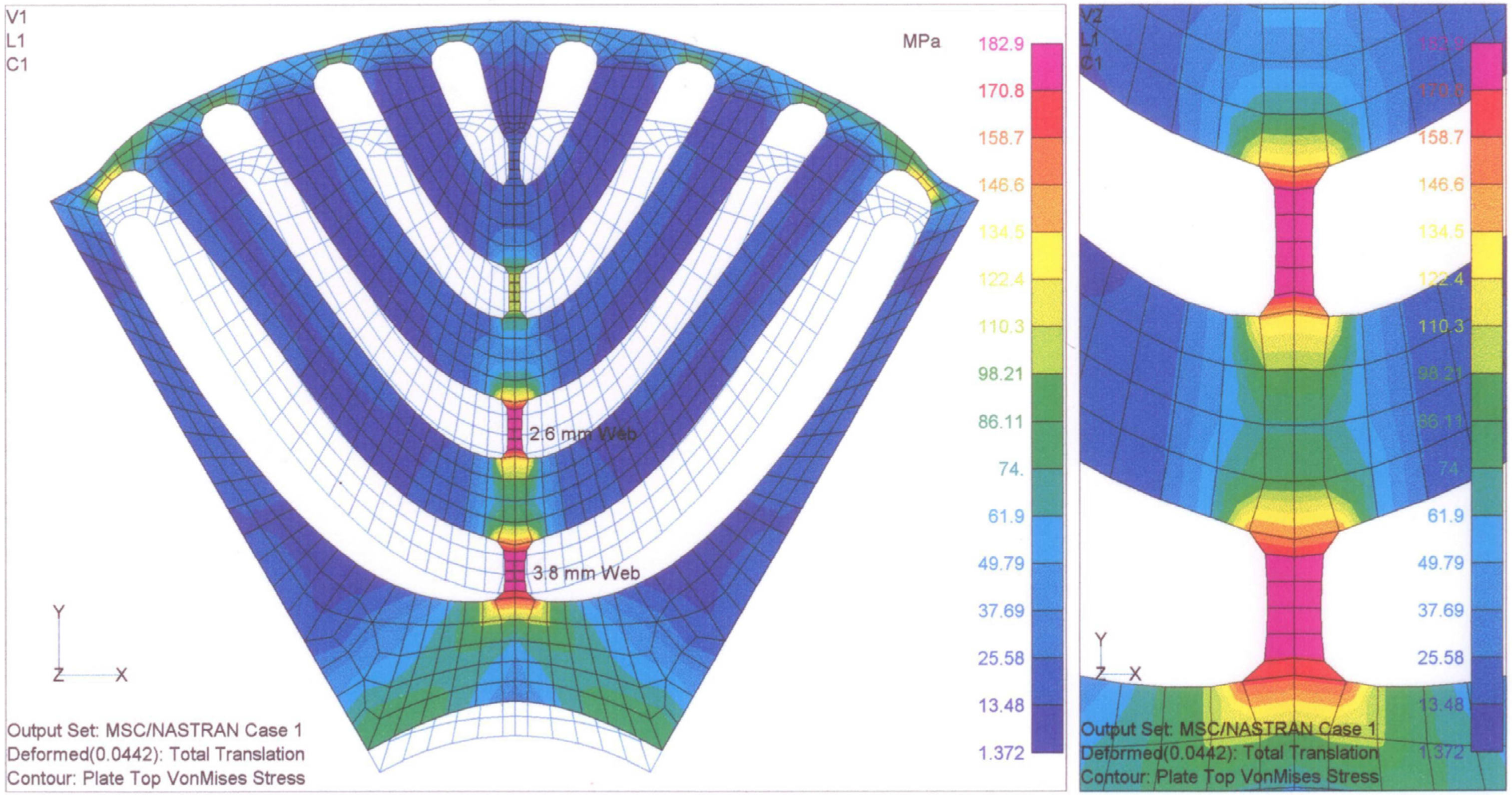
→ Rather no iron webs

Design



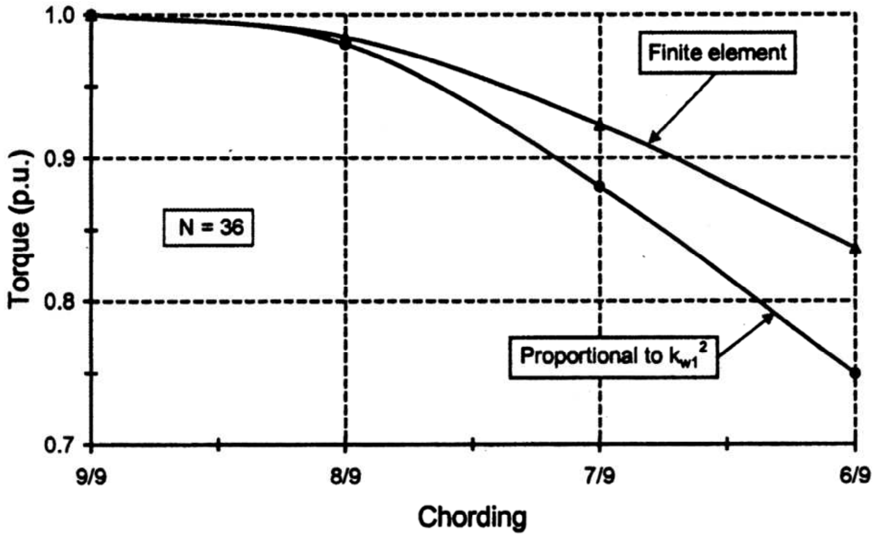
→ Reducing torque ripple without skewing

Sanada, Morimoto, 2004; Bianchi, 2006

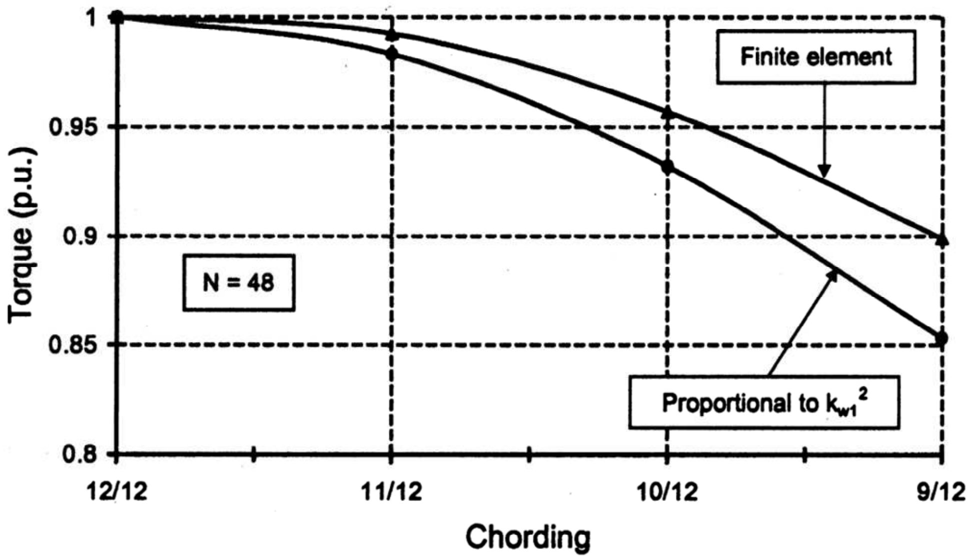


Von Mises Stress Distribution due to 4500 rpm Rotation on Deformed Model (Blown-up)

Design

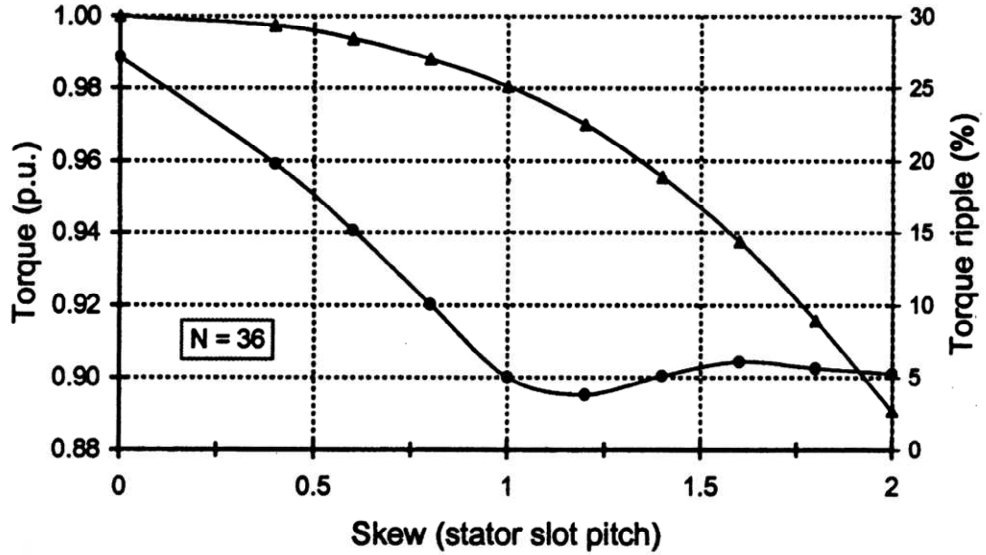


9 kW

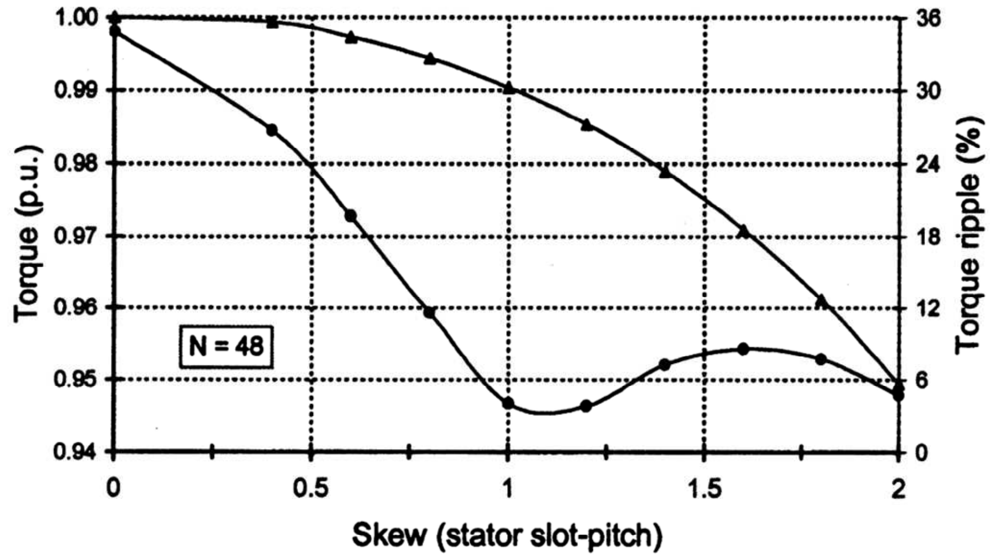


42 kW

Design

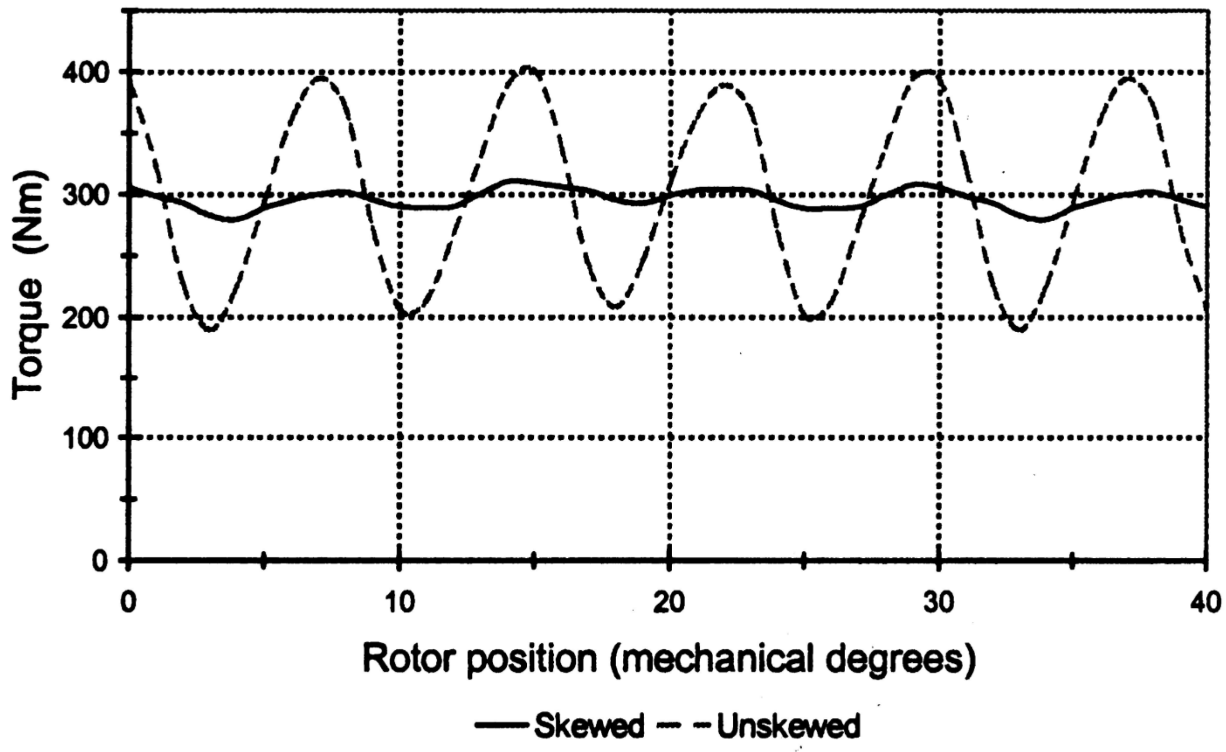


9 kW



42 kW

Design



42 kW

Bomela, X. and Kamper M.J.: "Effect of stator chording and rotor skewing on performance of reluctance synchronous machine", IEEE Trans. Ind. Appl. Soc. (IAS), vol. 38, no. 1, pp. 91-100, Jan. **2002**.

Design

2-pole

4-pole

6-pole

?

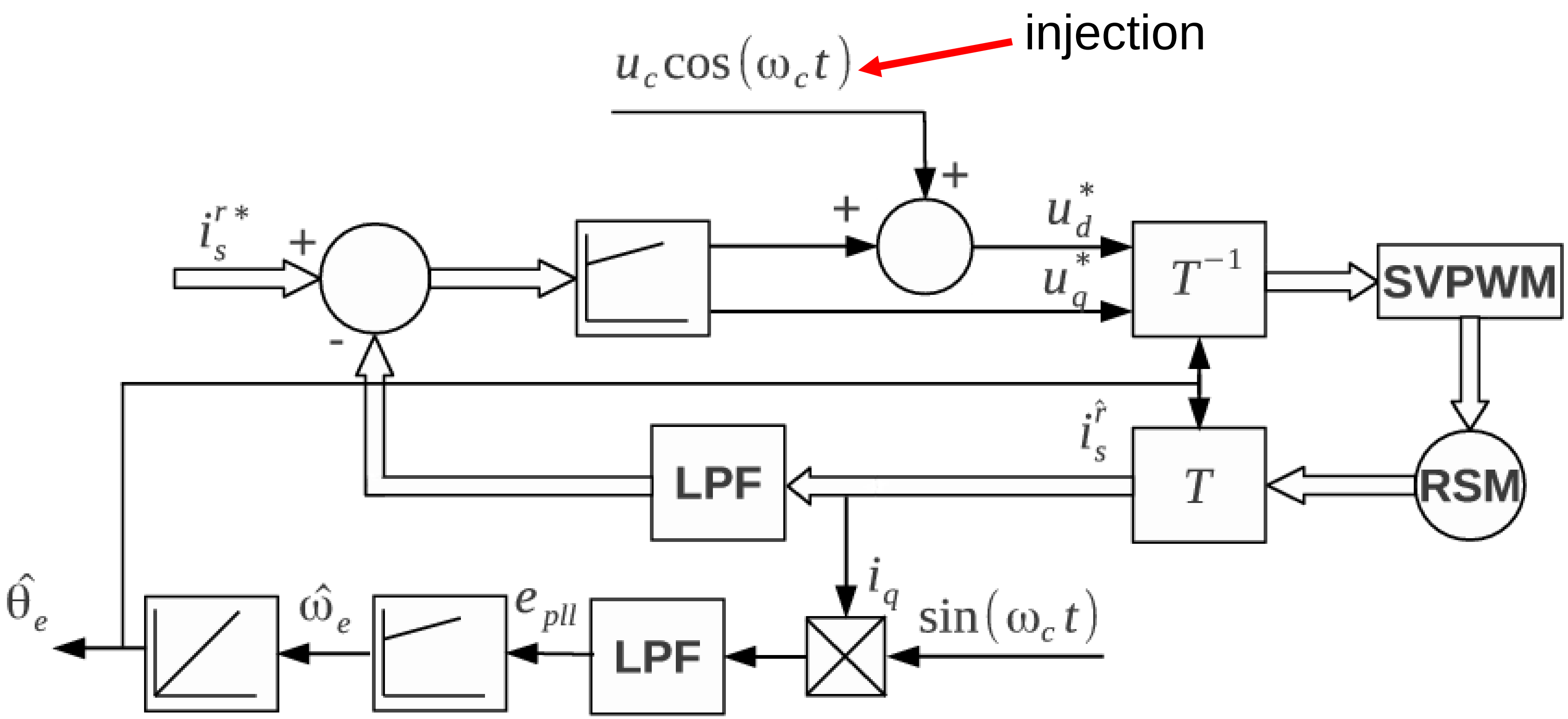
Position sensorless control

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

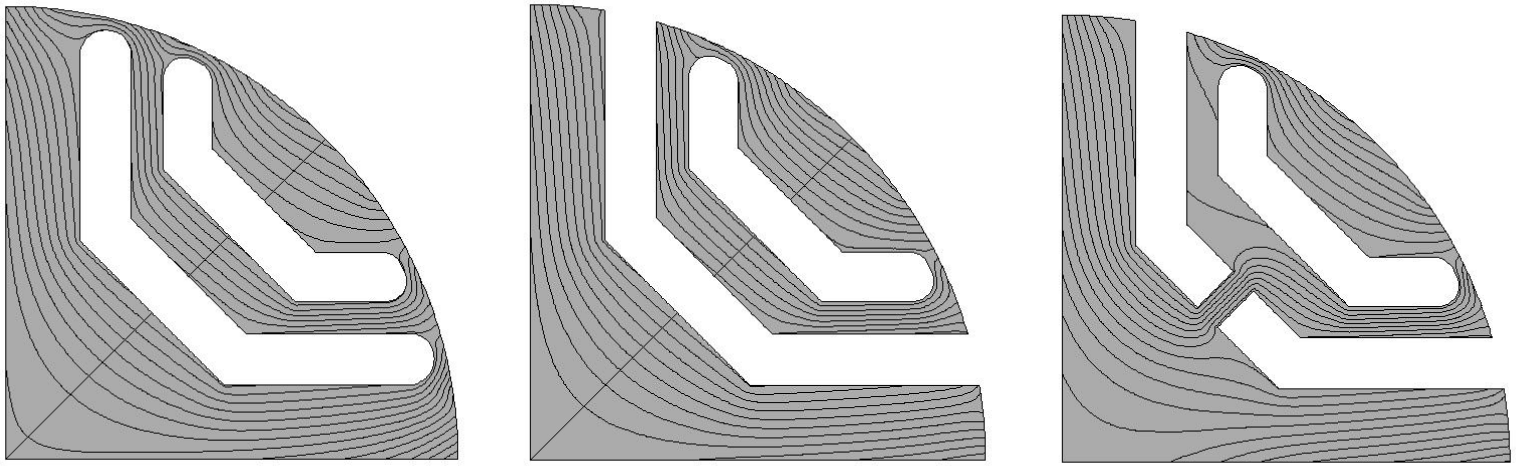
$$i^r_{sq(\text{demodulated})} \approx \frac{u_c L_\Delta \theta_\Delta}{L_d L_q \omega_c}$$

$$\text{Saliency} \rightarrow \quad L_\Delta = \frac{L_d - L_q}{2}; \qquad \text{Position error} \rightarrow \theta_\Delta = \theta_e - \hat{\theta}_e$$

$$L_d = \frac{\partial \psi_d}{\partial i_d}; \qquad L_q = \frac{\partial \psi_q}{\partial i_q}$$

→ Saliency is load dependent

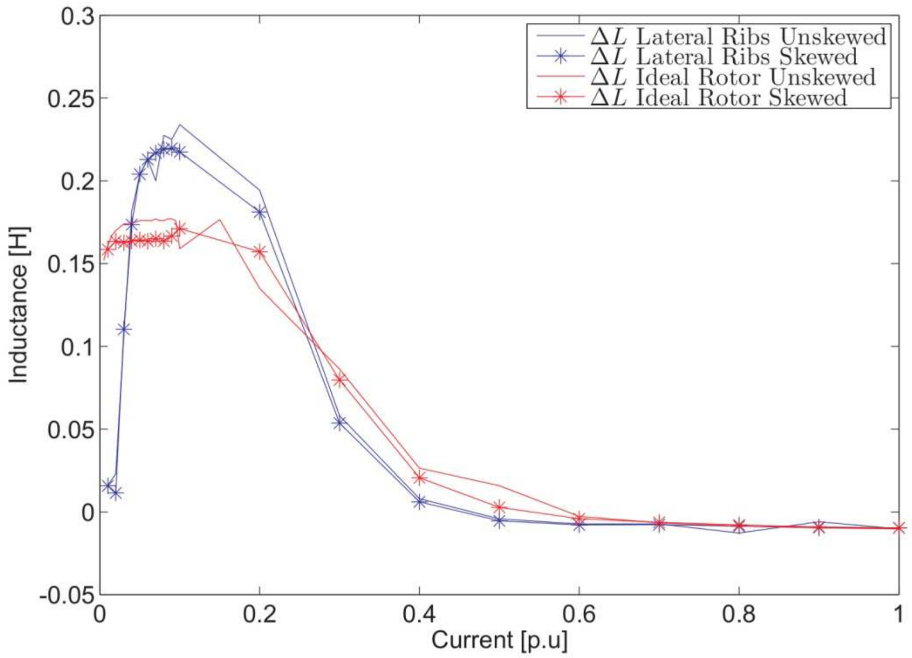
Position sensorless control Effect of rotor design



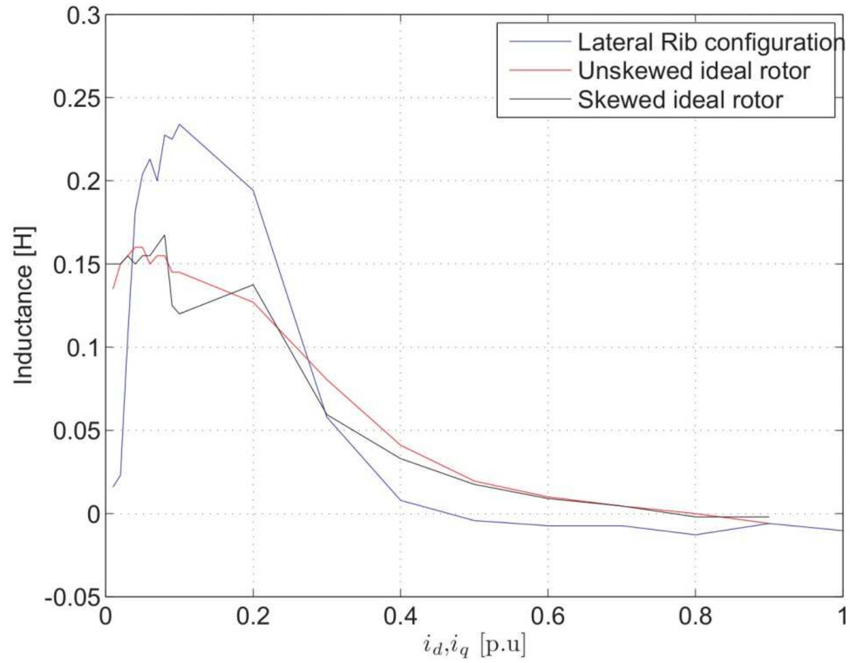
Normal with ribs | Ideal

Villet (2013) W. and Kamper M.J.: “Design of a RSM for saliency based position sensorless control at zero current", IEEE Int. Conf. on Industry Technology (ICIT), Cape Town (SA), 25-27 Feb, 2013.

Position sensorless control Alternating injection



Simulated



Measured

Villet (2013) W. and Kamper M.J.: "Design of a RSM for saliency based position sensorless control at zero current", IEEE Int. Conf. on Industry Technology (ICIT), Cape Town (SA), 25-27 Feb, 2013.

Frenzke, EPE (Dresden) 2005

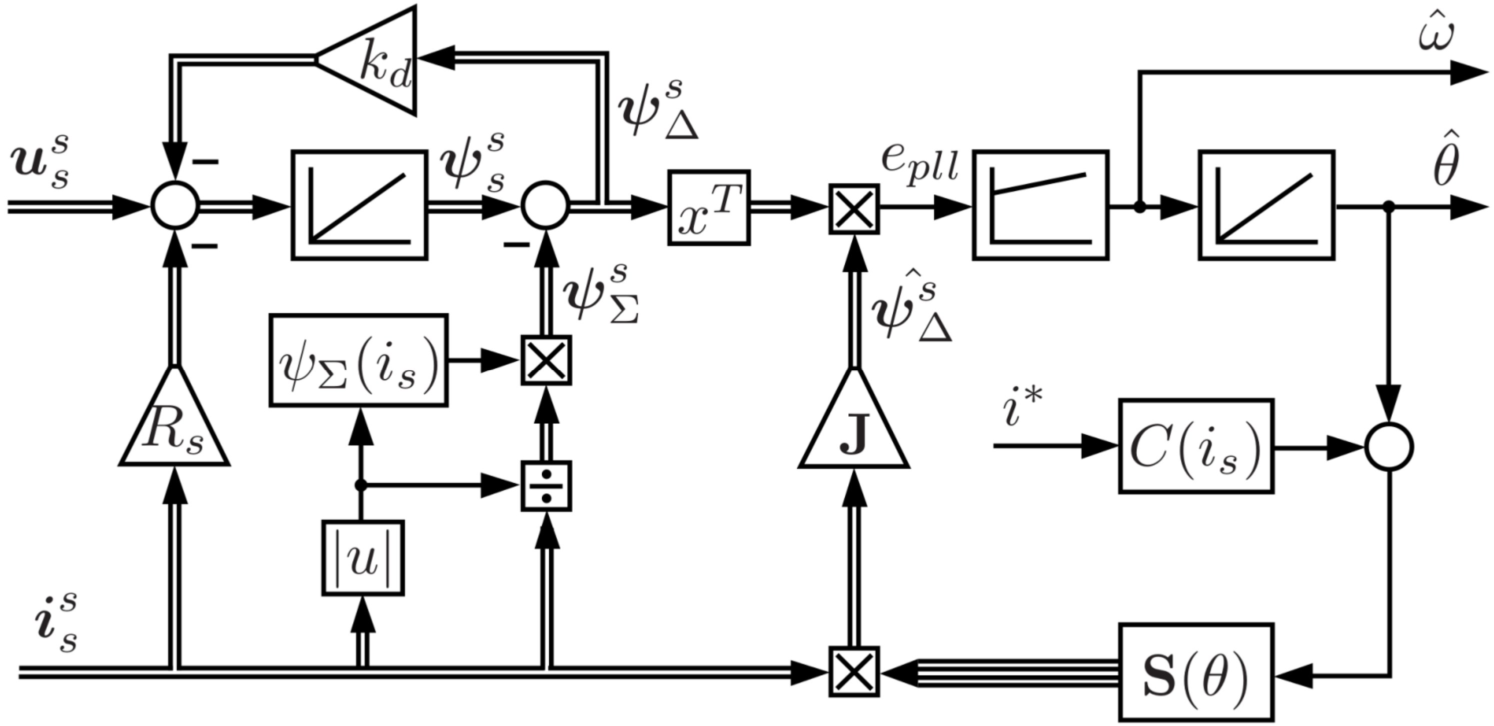
Magnetic axis shift (real position error)

$$\theta_{\Delta 0} = -\frac{1}{2}\tan^{-1}\left(\frac{2L_{dq}}{L_d - L_q}\right) \quad \text{with} \quad L_{dq} = \frac{\partial \psi_d}{\partial i_q}$$

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

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

Position sensorless control



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):

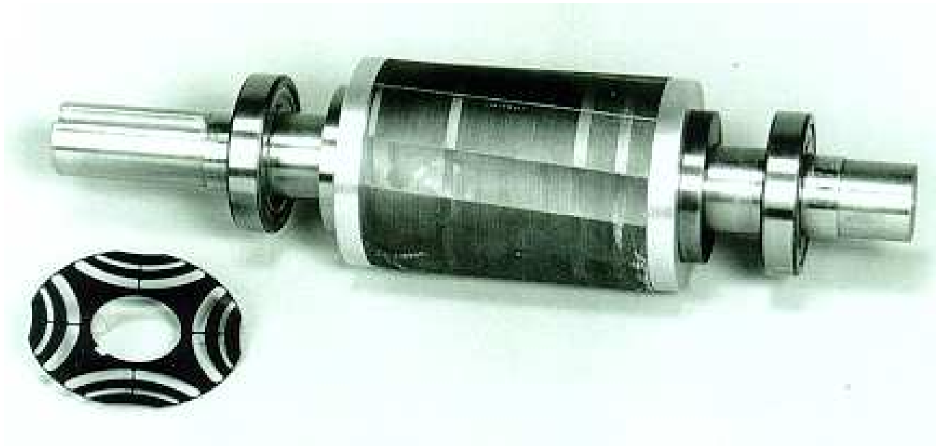
- Almost no effect on efficiency and thermal.
- No higher audible noise with sensorless FOC.
- Rotor skewing is no problem with sensorless control.
- Rated standstill torque could be obtained sensorless.
- Sensorless with low to zero load current ? → need alternative rotor design and manufacturing.

W.T. Villet and M.J. Kamper, "Evaluation of reluctance synchronous machine rotor topologies for position sensorless control", Southern African Universities' Power Engineering Conference (SAUPEC), Potchefstroom, Jan 31 – Feb 1, 2013

Manufacturing + Performance

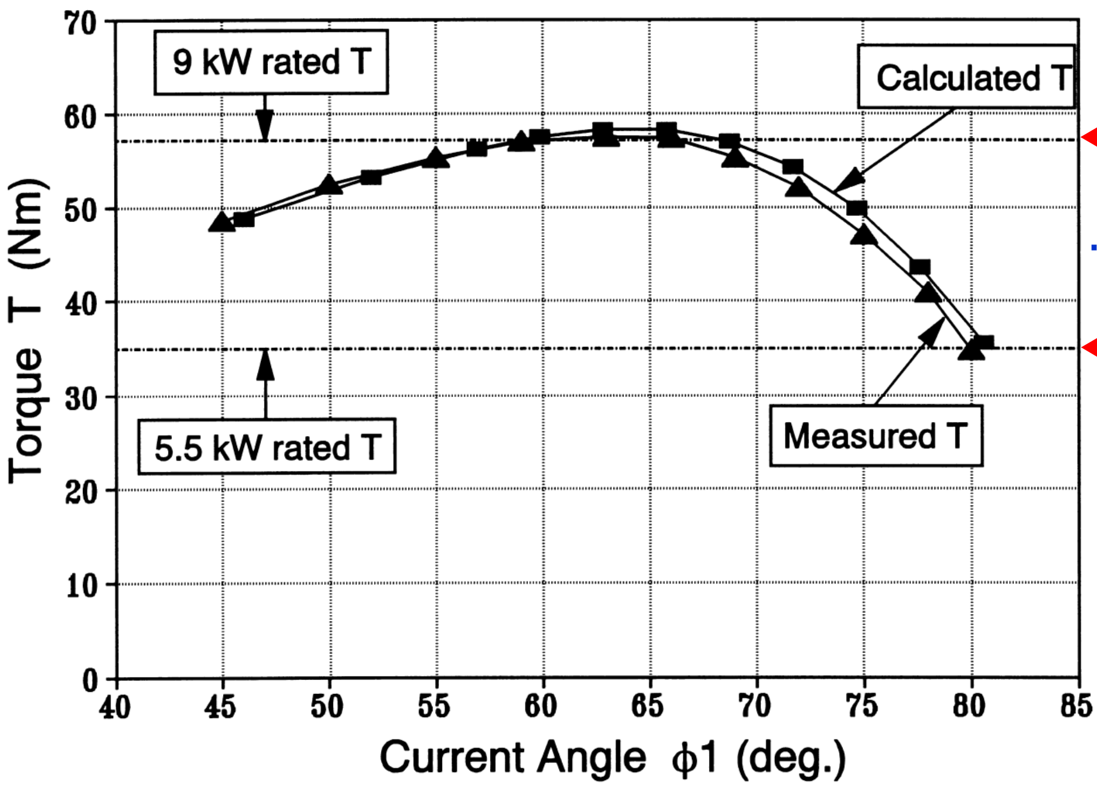
9 kW RSM

2.8 kW DC
2.2 kW IM
9 kW RSM



9 kW @ 1500 r/min RSM rotor - skewed

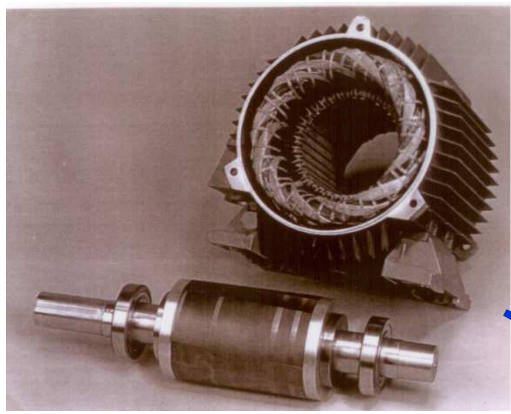
Manufacturing + Performance 9 kW RSM



9 kW RSM

… in same casing!

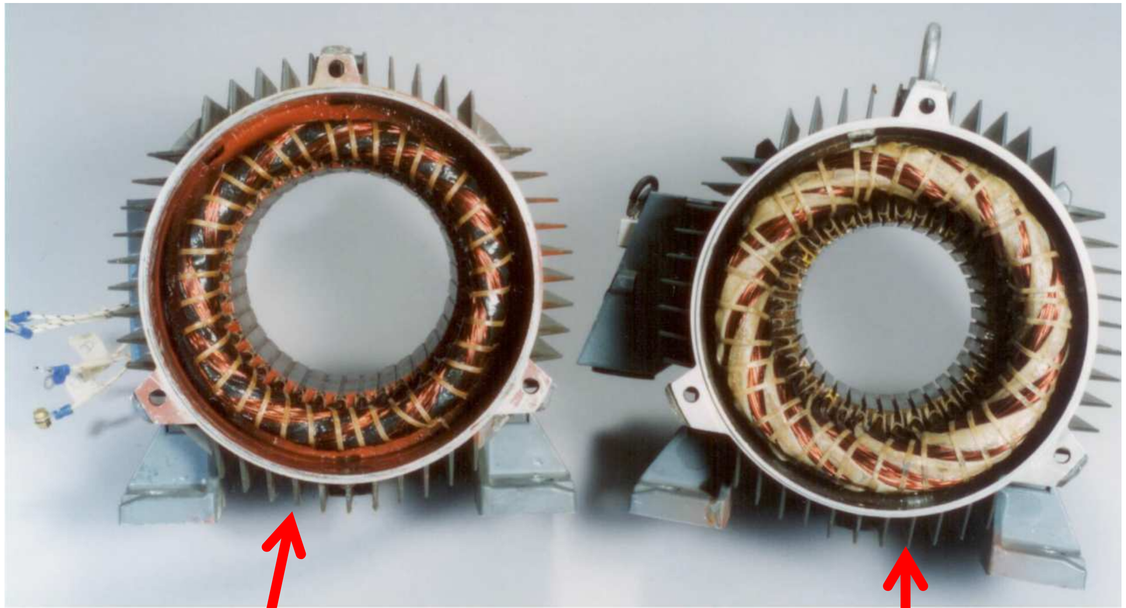
5.5 kW Induction Machine

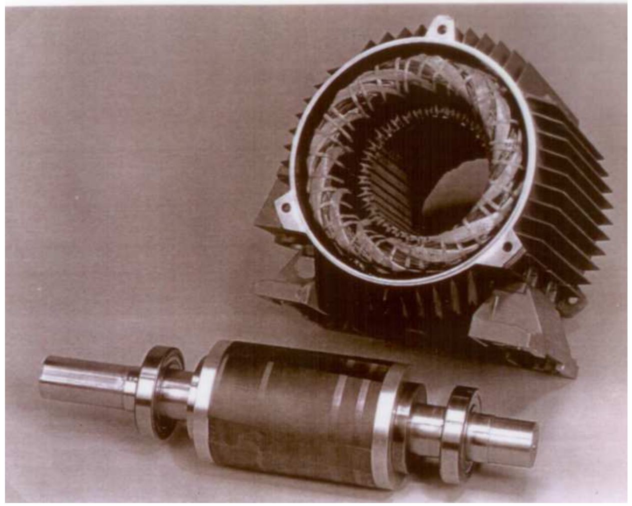


Kamper M.J., Van der Merwe F.S. and Williamson S.: "Direct finite element design optimisation of the cageless reluctance synchronous machine", IEEE Trans. on Energy Conversion, Vol. 11, No. 3, September **1996**, pp. 547-553.

Manufacturing + Performance

9 kW RSM



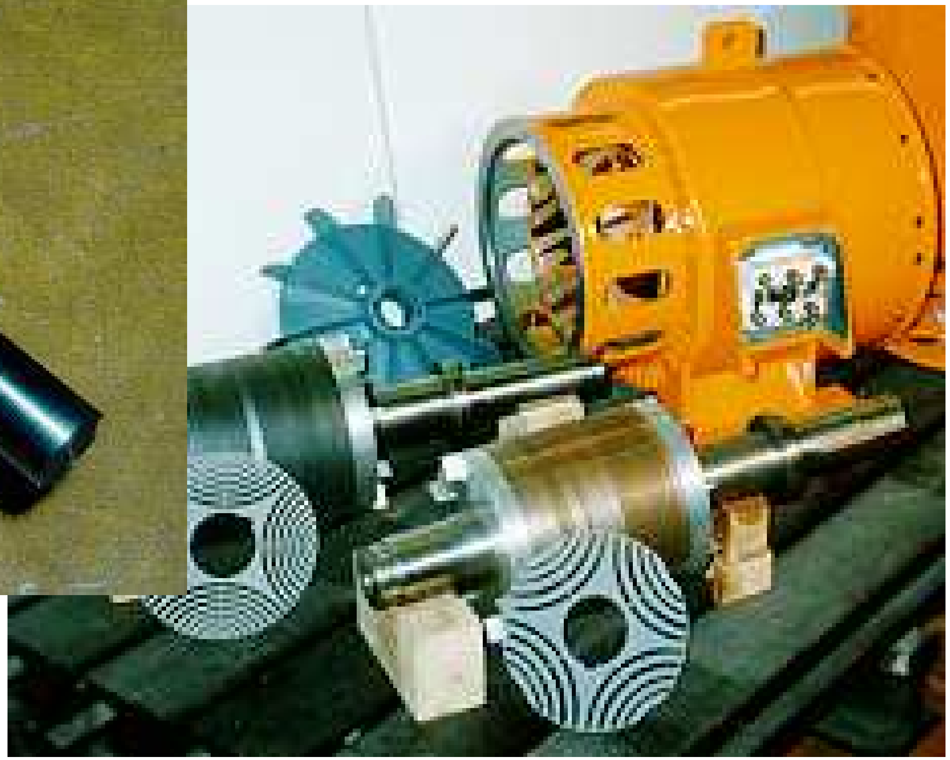


5.5 kW standard line started Induction Machine – stator and casing

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

Manufacturing

42 kW RSM



Manufacturing

Loher 30 kW RSM

Performance tests

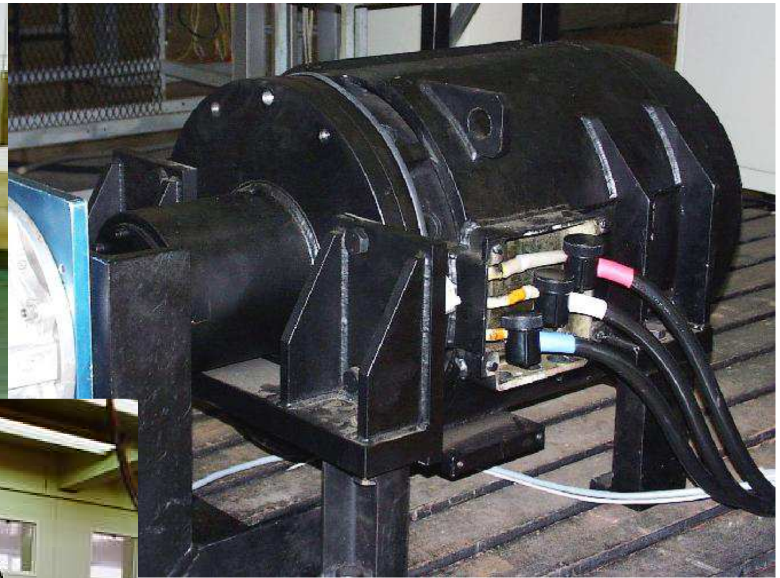
Loher 30 kW RSM

Abbildung 2 Prüfstand im IM Prüffeld zur Messung des RSM

	Airgap	Current	Voltage	Pout	Effciency	Tempr.
IM	0.7 mm	55.4 A	400 V	30 kW	91.7	59 K
RSM	0.6 mm	52.5 A	457 V	28.3 kW	93.8	45 K

Manufacturing

110 kW RSM

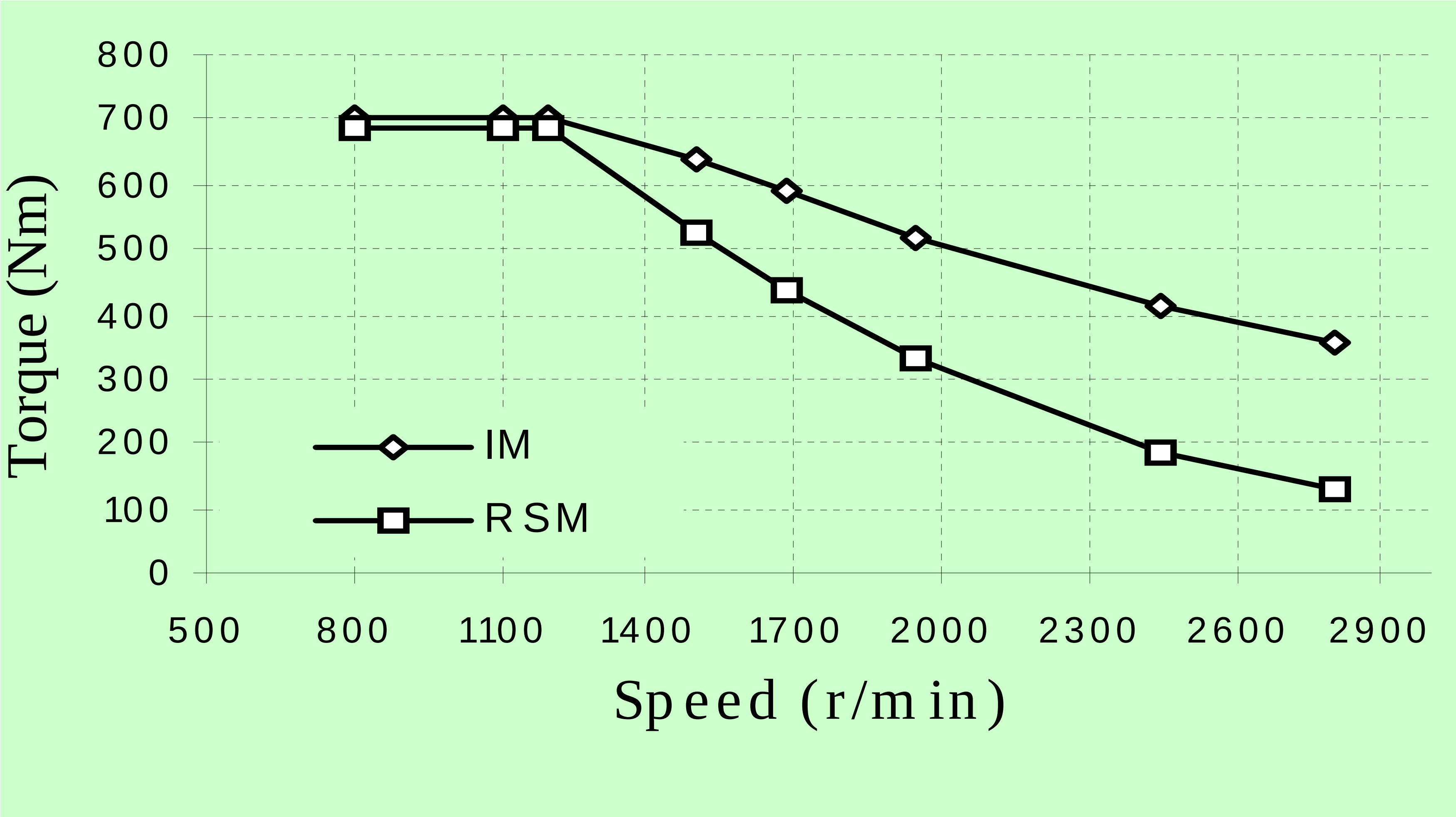


Manufacturing

Locally manufactured 110 kW RSM Rotor

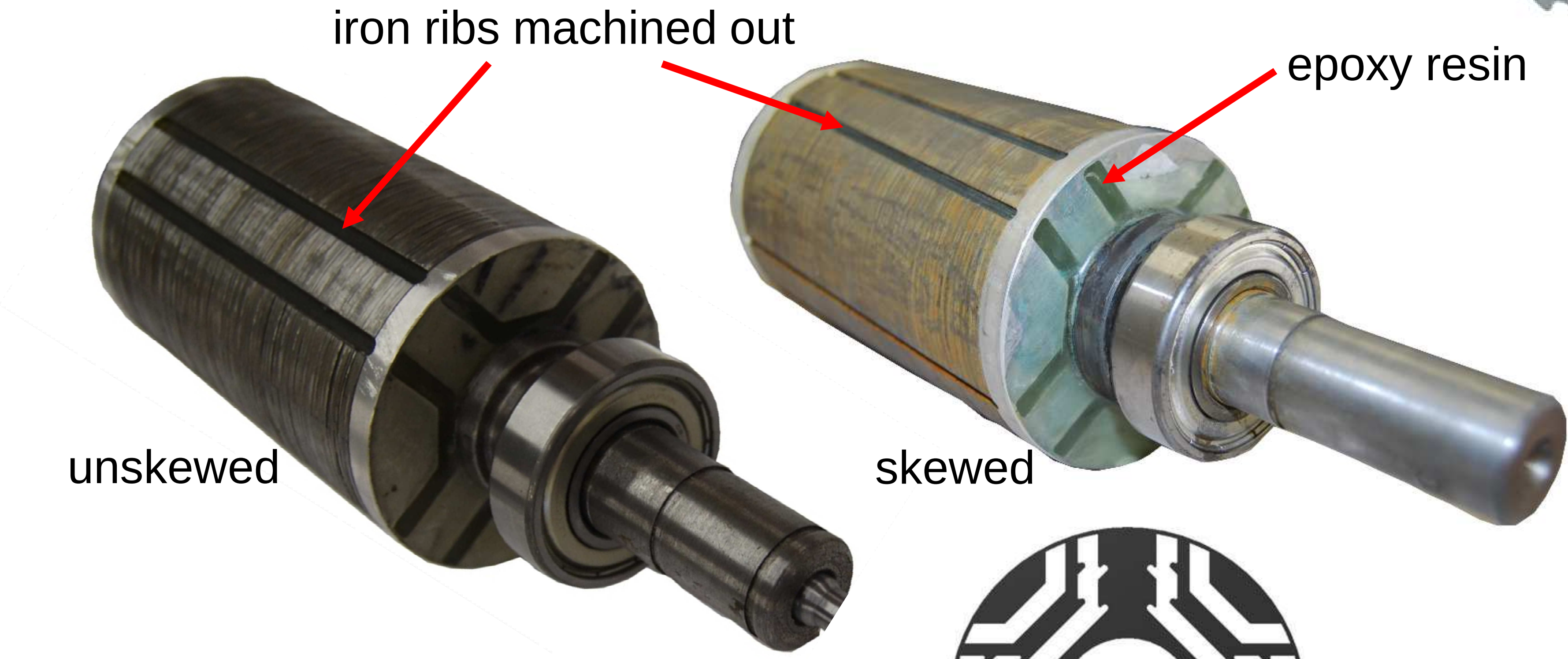
Performance tests

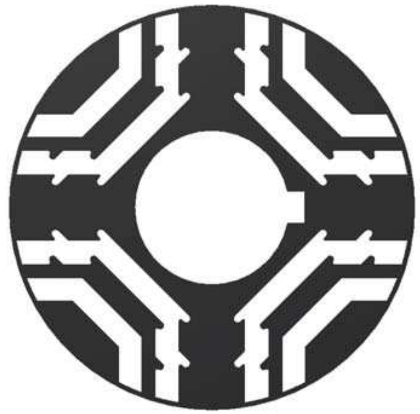
110 kW RSM



Manufacturing

Epoxy casted

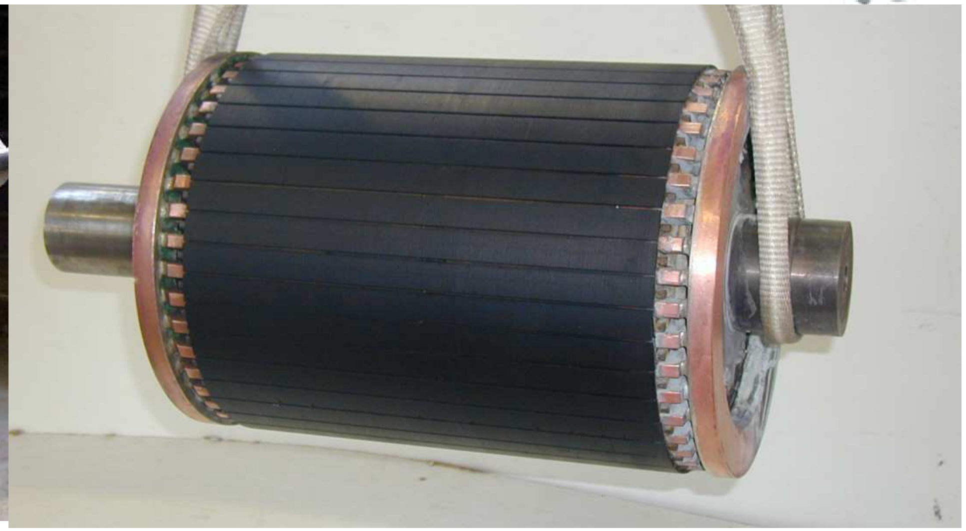




Villet (2013) W. and Kamper M.J.: “Design of a RSM for saliency based position sensorless control at zero current", IEEE Int. Conf. on Industry Technology (ICIT), Cape Town (SA), 25-27 Feb, 2013.

Cost

Rotor manufacturing

- 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 ?

ABB

Data


100%
80-90%
I²R Rotor
Other
I²R Stator
Other
I²R Stator
Traditional induction motor
Losses
High output SynRM motor

ABB

Data

Pump application example 22 kW, 1500 rpm		
	High output SynRM motor	**ABB IE2 induction motor**
Frame size	160, 174 kg	180, 222 kg
Motor efficiency	DOL: N/A, VSD: 92.8%	DOL: 92.4%, VSD: ~91.0%
		

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

Fan application example 37 kW, 3000 rpm		
	High output SynRM motor	**ABB IE2 induction motor**
Frame size	160, 157 kg	200, 298 kg
Motor efficiency	DOL: N/A, VSD: 93.7 %	DOL: 93.4%, VSD: ~92.2%
	 Free area: 65%	 Free area: 25%

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

ABB

… slide 46 confirms this statement

… quotes

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

The low temperature operation improves the lifetime of the motor insulation, and extends the bearing lifetime or greasing intervals.

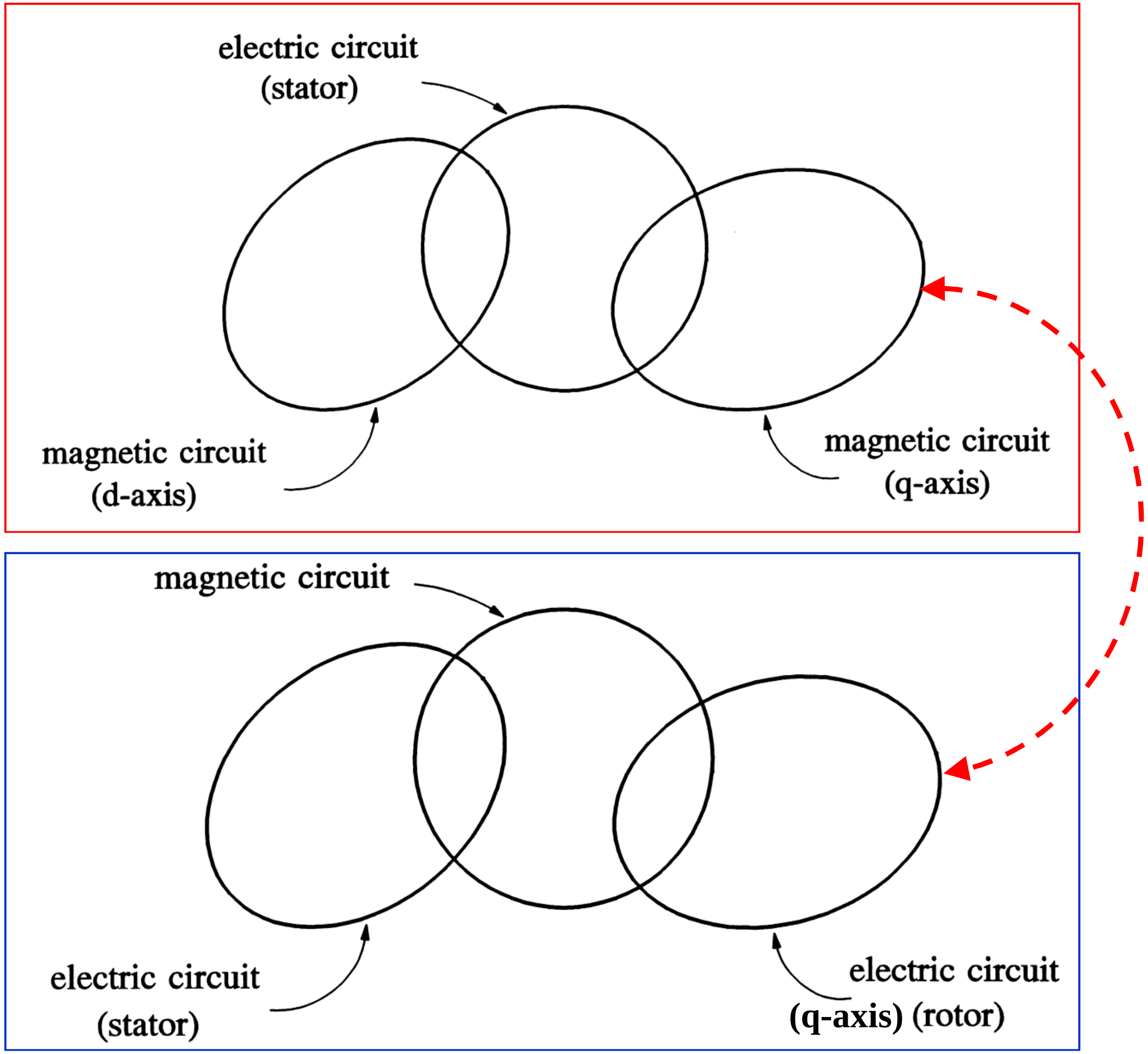
Since there is always a frequency converter between the motor and the grid, the lower power factor is not apparent on the grid side and consequently does not have an impact on the grid supply dimensioning. However, the lower power factor may sometimes mean that a frequency converter with a higher current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

… important statement

RSM / IM working Electric and magnetic circuits

RSM →

IM →



the difference in q-axis circuits explain the differences between the machines

Some other questions

→ Audible noise of RSM drives ?

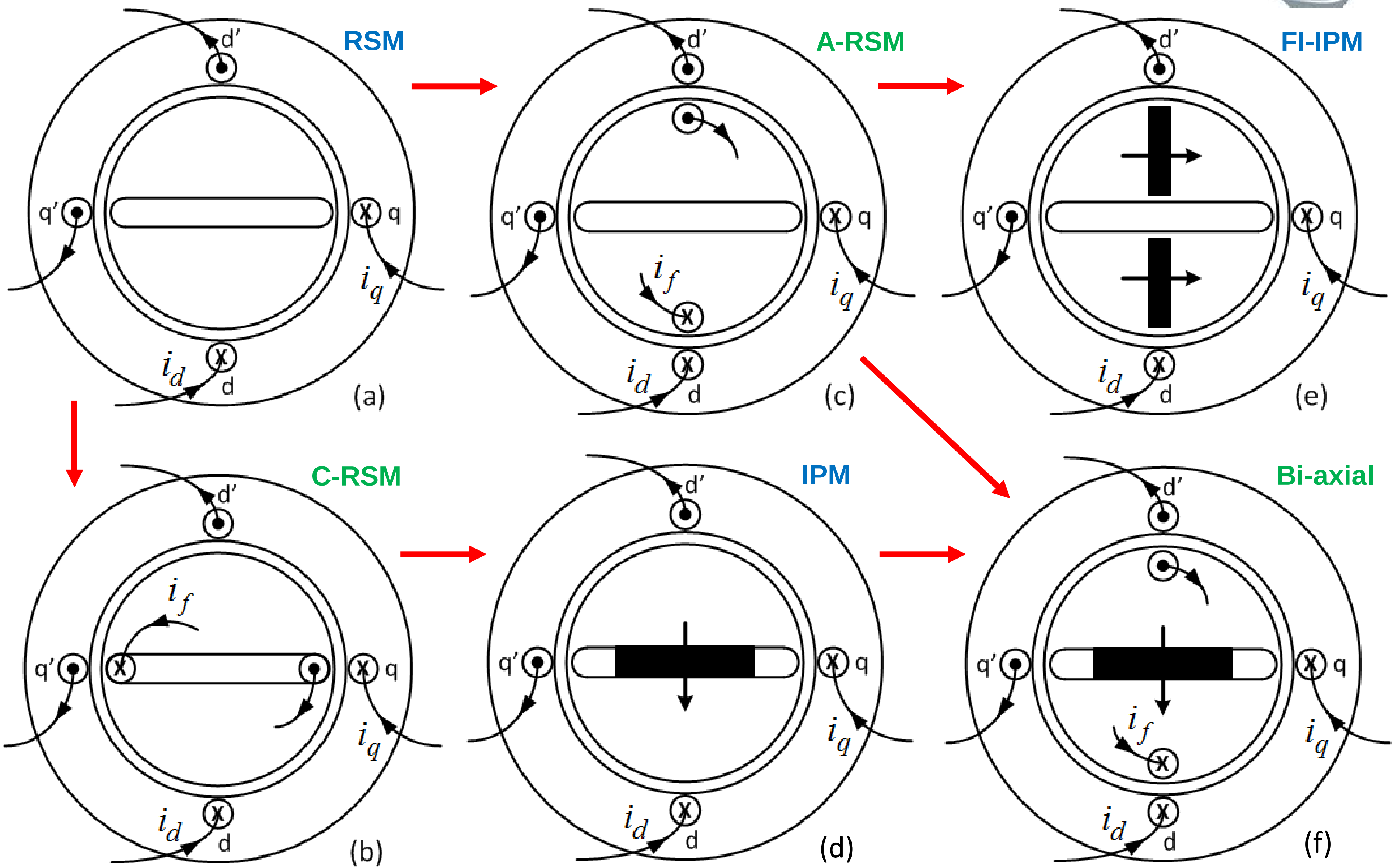
… this seems not to be an issue.

→ Bearing currents in converter-fed RSMs ?

… are bearing currents worse than e.g. in the IM drive ?

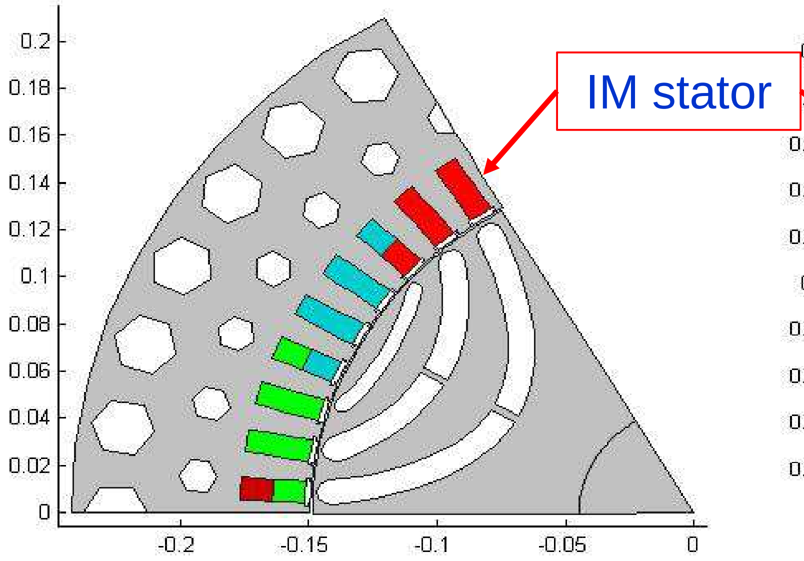
Assisted RSMs

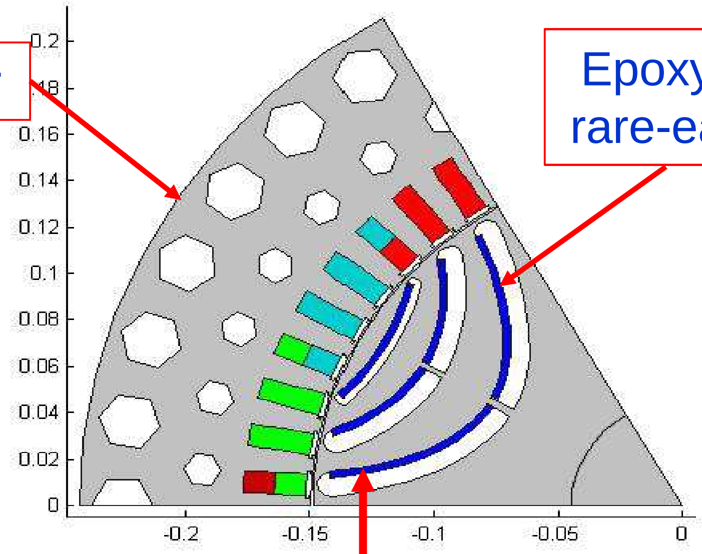
IPM, FI, WR

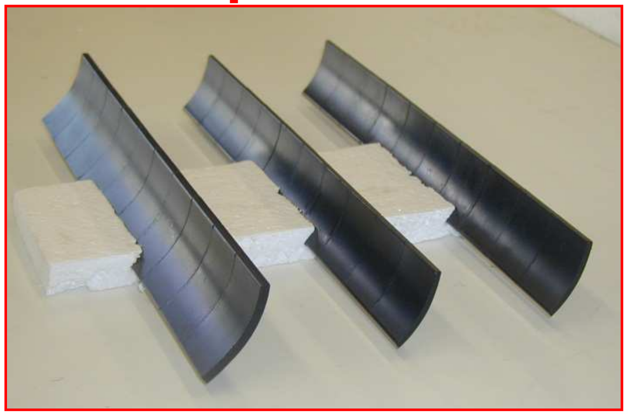


Assisted RSMs

IPM

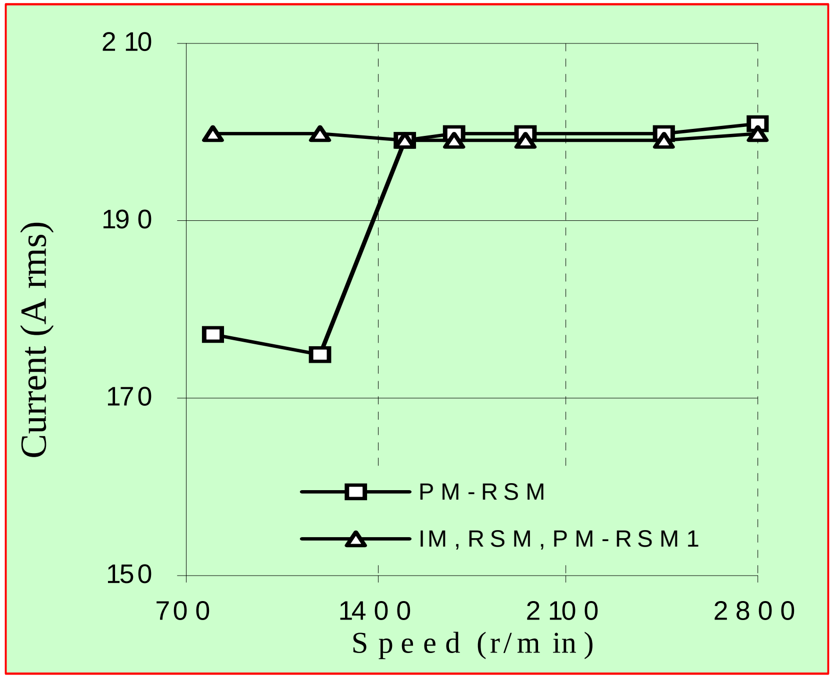


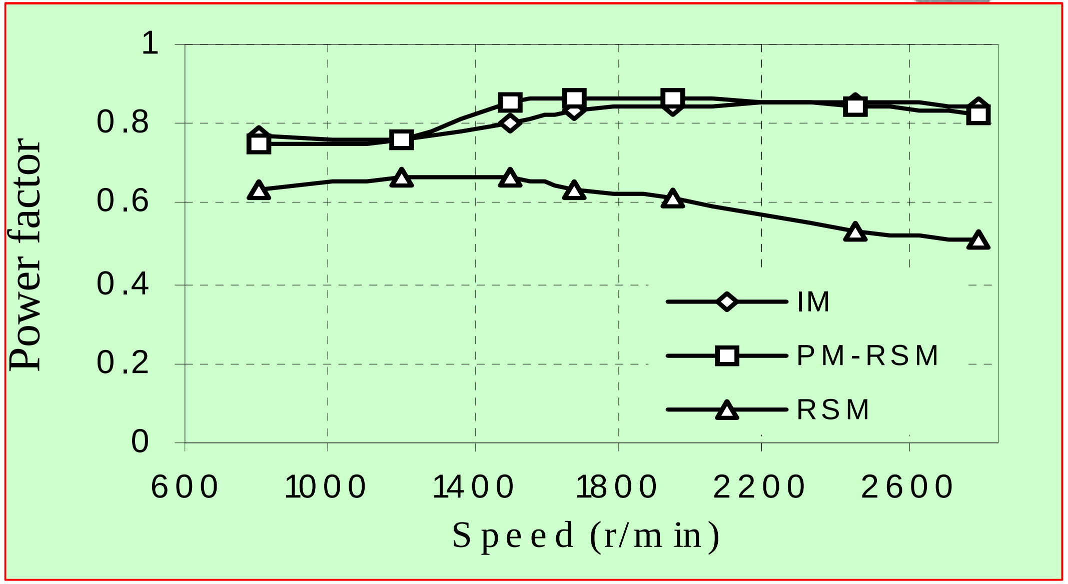


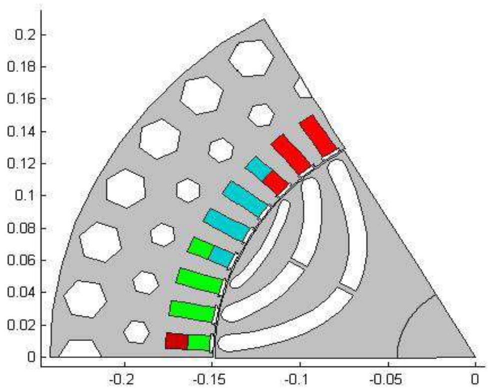


Comparison

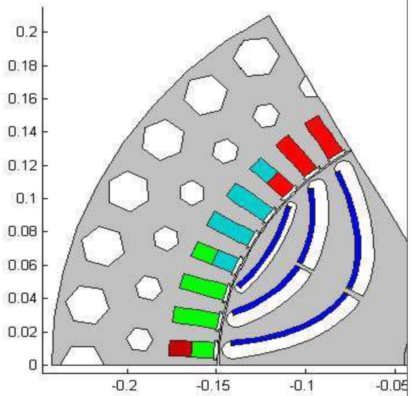
RSM, IM, PM-RSM



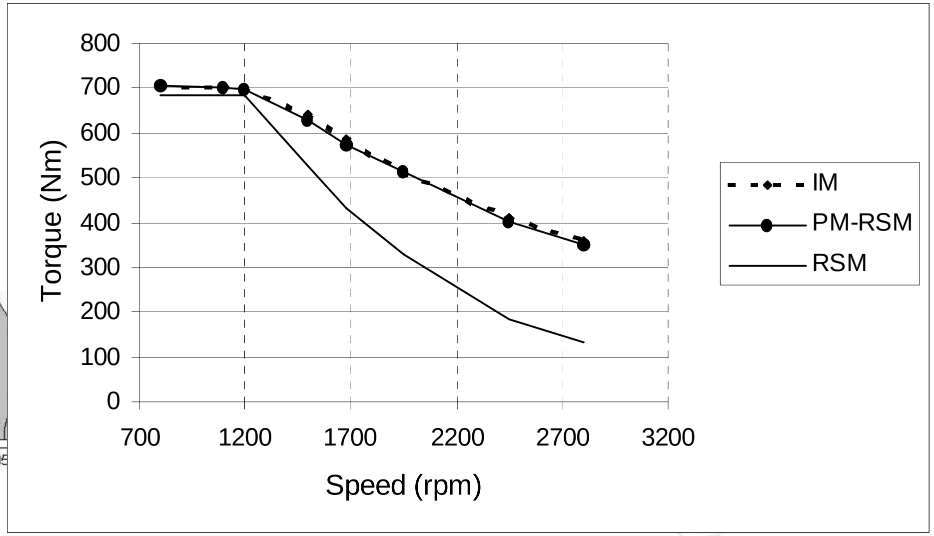




RSM

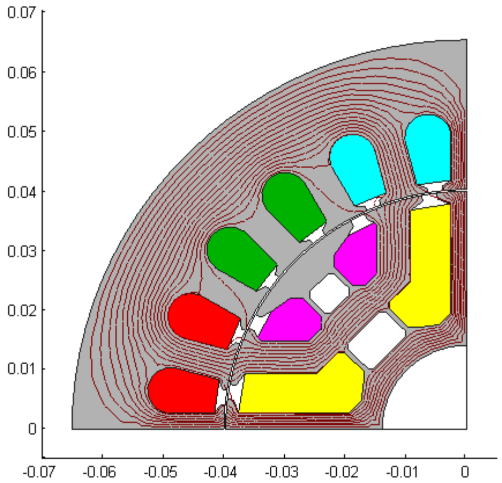


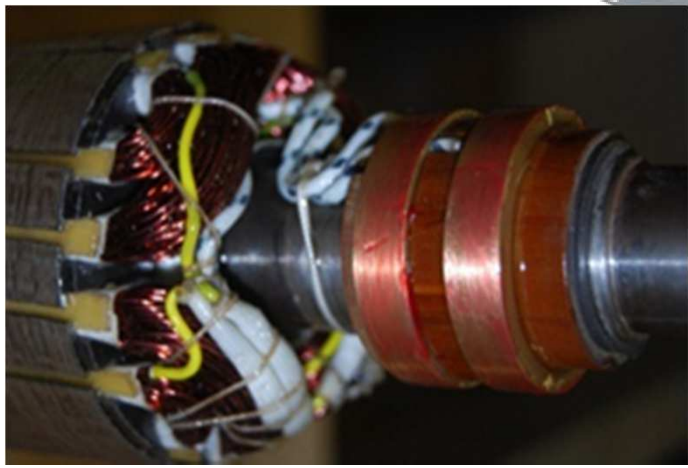
PM-RSM

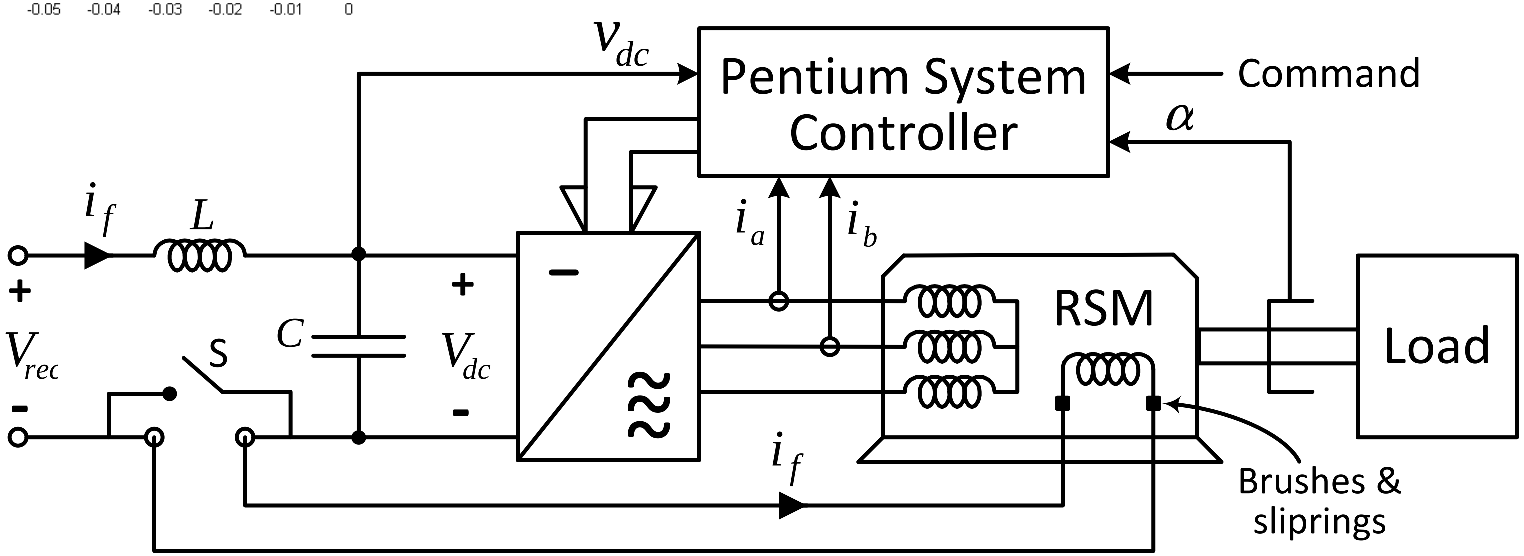


Assisted RSMs

Wound rotor

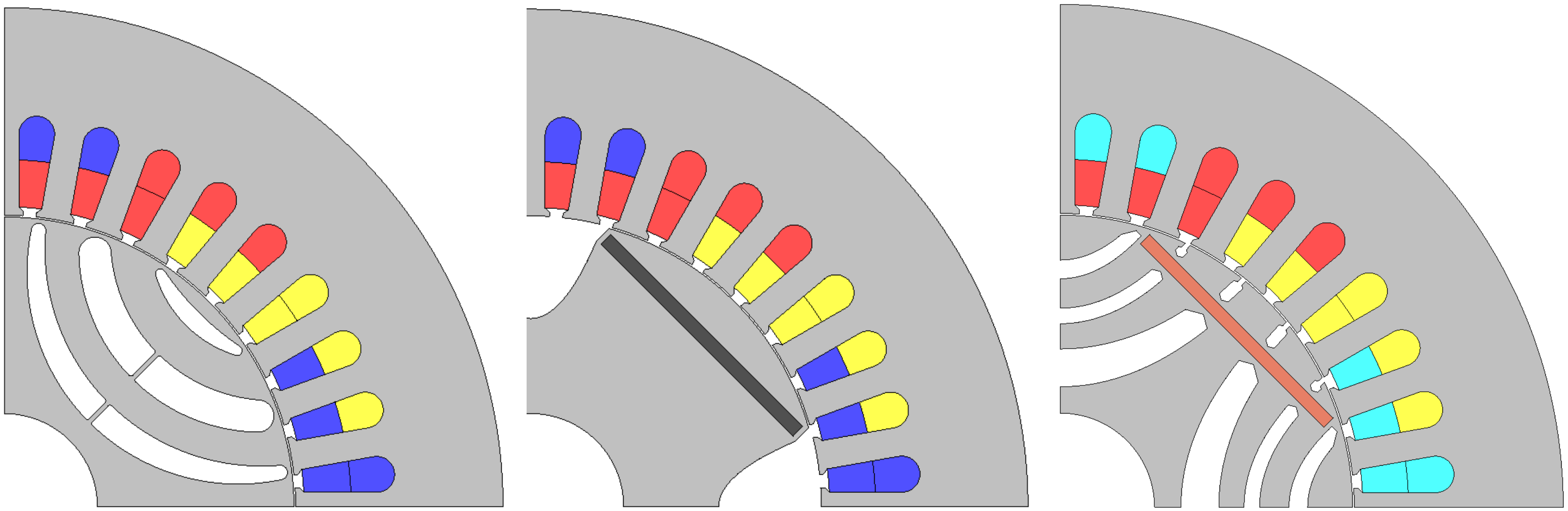






Kamper M.J. en Villet W.: "Design and performance of compensated reluctance synchronous machine drive with extended constant power speed range", IEEE ECCE, Raleigh (USA), Sept. 15-20, 2012.

Assisted RSMs



	RSM	FI-IPM	FI-IPM
p.u. stack volume for the same power →	1.0	1.0	0.8

M.H.A. Prins, C.W. Vorster and M.J.Kamper, "Reluctance synchronous and field intensified-PM motors for variable-gear electric vehicle drives", IEEE ECCE, Denver (USA), 15-19 Sept, 2013.

Conclusions

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 totday is extremely important and RSM drives have that advantage.
- RSM position sensorless control is viable for certain small and medium power VSD applications.

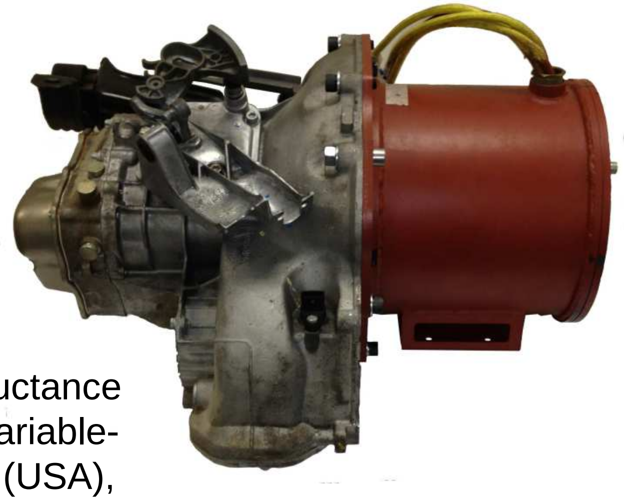
Conclusions

- 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

- Multi-gear EV drives



M.H.A. Prins, C.W. Vorster and M.J.Kamper, "Reluctance synchronous and field intensified-PM motors for variable-gear electric vehicle drives", IEEE ECCE, Denver (USA), 15-19 Sept, 2013.

- RSG high speed windgenerators ?

Thank You for Your Attention

Vielen Dank für Ihre Aufmerksamkeit

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