Some Comments on the Present and Future Direction of Electrical Machine Research

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The Issue

For the Last 20 Years Electrical Machine Design Has Been Enjoying a Renaissance With New Topologies Being Proposed Each Year.

The first of these, “Switched Reluctance” Machines Was Proposed in 1980, 36 years ago.

Since then 3,200 papers on this Topic have Appeared According to the IEEE Explorer

Very Few, If Any Have Attempted to Compare this Machine with More Conventional AC Machines

The Issue

The “Renaissance Era” Began in 2005 With
The Introduction of the “Switched Flux” Machine

Since 2005 over 620 Papers Have Been Written on
This New Topic (56 per year!)

Again, No Serious Effort Has Been Made to Compare
This Machine with More Conventional AC Machines
Such as Wound Field Synchronous and PM Machines

Other Structures Appearing Almost Yearly Are Invariably Never
Evaluated Against Any Commonly Accept Frame of Reference

There is a Serious Need for a Sanity Check!

Issues Related to Comparison of Machines

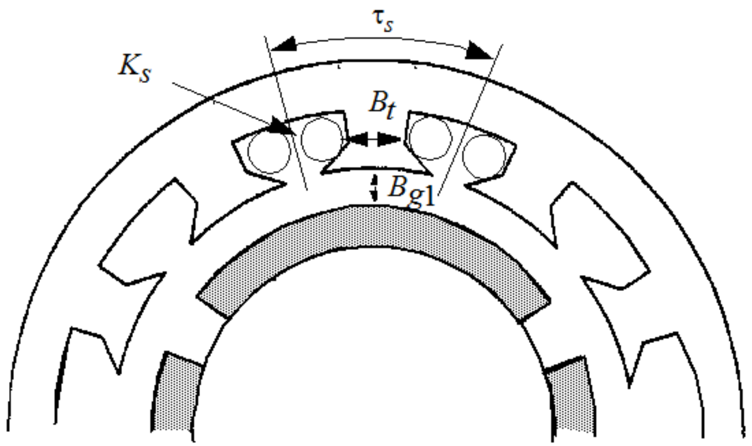
Problems:

- Current Generally Not Sinusoidal
- Air Gap Flux Density Not Sinusoidally Distributed

Solution:

- Use RMS Value of Surface Current Density
- Use the Stator Tooth Flux Density As a Figure of Merit, Not Gap Flux Density

Essen's Torque Expression



B_{g1} – Peak Air Gap Flux Density (Fundamental Component) T.

K_s – Surface Current Density (Peak Fundamental Component) A/m

The Torque for a Synchronous or PM Machine
Can be Expressed As:

$$T_{synch} = \frac{4}{\pi} k_1 K_s B_{g1} (D_{is}^2 L) \cos\varepsilon$$

(ε typically set to zero by means of control)

(pitch/distribution k_1 factor set to unity for convenience)

A More Generally Applicable Torque Expression

Assuming

$$K_{s(rms)} = \frac{K_s}{\sqrt{2}}$$

and

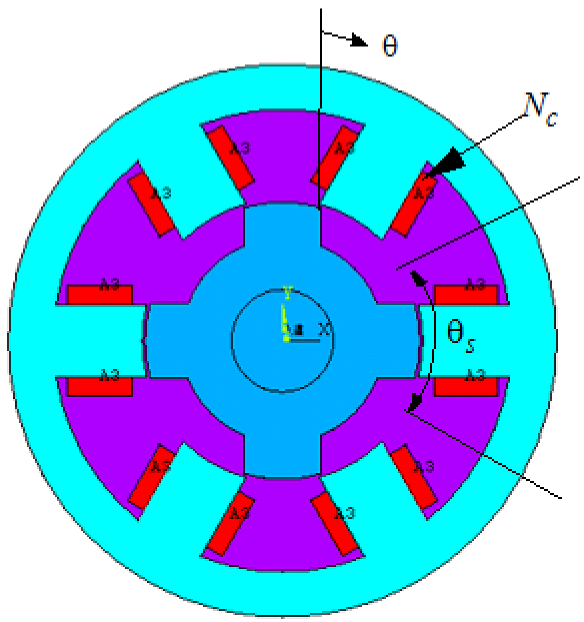
$$B_t = 2B_{g1}$$

The Resulting Modified Essen's Torque Equation

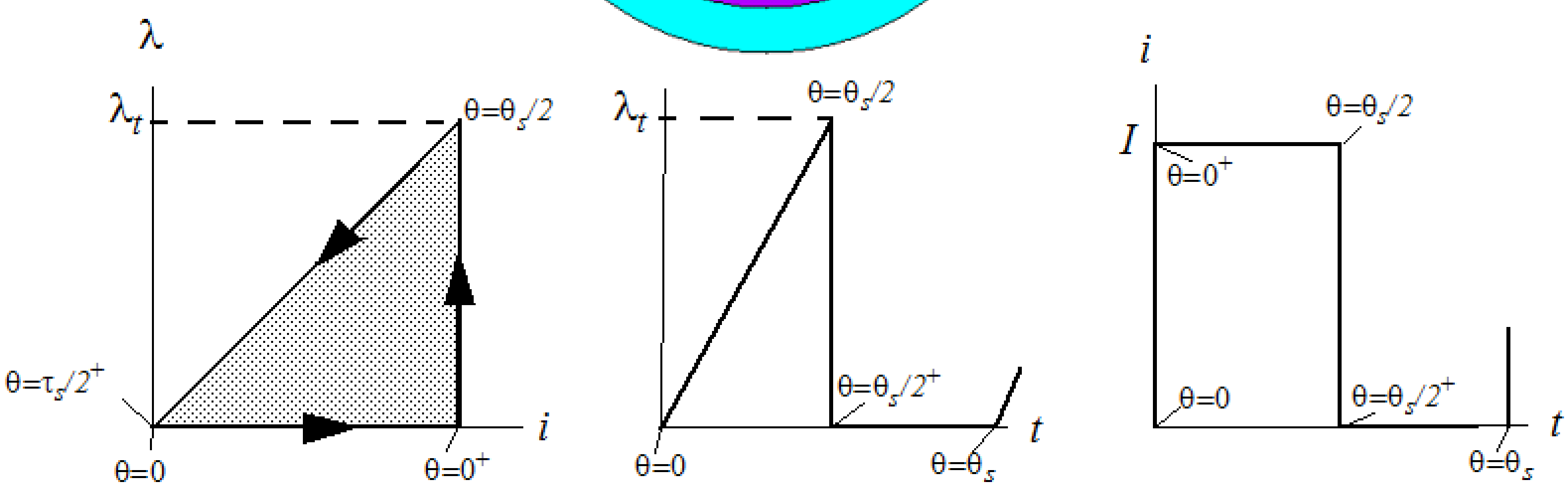
for Synchronous and PM Machines Becomes (k_1=1, ε=0)

$$T_{synch} = \frac{2\sqrt{2}}{\pi}(D_{is}^2 L)K_{s(rms)}B_t$$

Switched Reluctance Machines



$$\tau_s = \frac{\pi D_{is}}{P_s}$$



Switched Reluctance Machines

$$\lambda_t = N_c B_t A_t = N_c B_t \left(\frac{\tau_s L}{2}\right)$$

$$\Delta\lambda_t = \lambda_t - \lambda_t(0) = \lambda_t$$

$$\Delta W = (\Delta\lambda_t) I = \frac{N_c B_t \tau_s L}{2} I$$

$$\frac{\Delta W}{\Delta t} = \frac{\Delta W}{\Delta\theta}\frac{\Delta\theta}{\Delta t} = \omega_r \frac{\frac{N_c B_t \tau_s L}{2} I}{\frac{1}{2}\left(\frac{2\pi}{P_r}\right)} = \frac{P_r}{2}\frac{\omega_r N_c B_t \tau_s L I}{\pi}$$

Switched Reluctance Machines

Over a half slot pitch $\tau_s/2$ or 1/2 cycle

$$T_{e1} = \frac{P_r}{2}\frac{N_c B_t \tau_s L I}{\pi}$$

Over a complete slot pitch τ_s or one cycle

$$T_{e1} = \frac{P_r}{4}\frac{N_c B_t \tau_s L I}{\pi}$$

But $\pi D_{is} = P_s \tau_s$

$$T_{e1} = \frac{1}{4}\left(\frac{P_r}{P_s}\right)(N_c B_t D_{is} L I)$$

Switched Reluctance Machines

Since there are P_s stator poles

$$T_e = P_s T_{e1} = \frac{P_r}{4}(N_c B_t D_{is} L I)$$

But

$$K_{s(rms)} = \frac{P_s N_c \left(\frac{I}{\sqrt{2}}\right)}{\pi D_{is}}$$

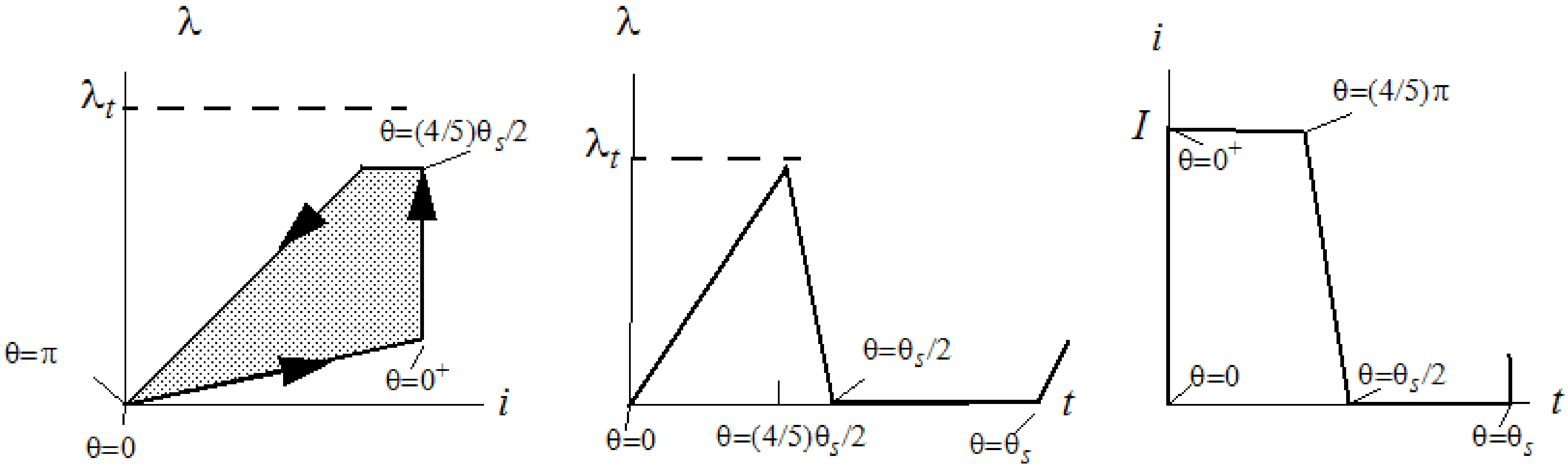
Thus

$$T_e = \frac{P_r}{4} N_c B_t D_{is} L \left(\frac{\pi D_{is} K_{s(rms)} \sqrt{2}}{P_s N_c}\right) = \frac{\sqrt{2}\pi}{4}\left(\frac{P_r}{P_s}\right) B_t K_{s(rms)} D_{is}^2 L$$

or

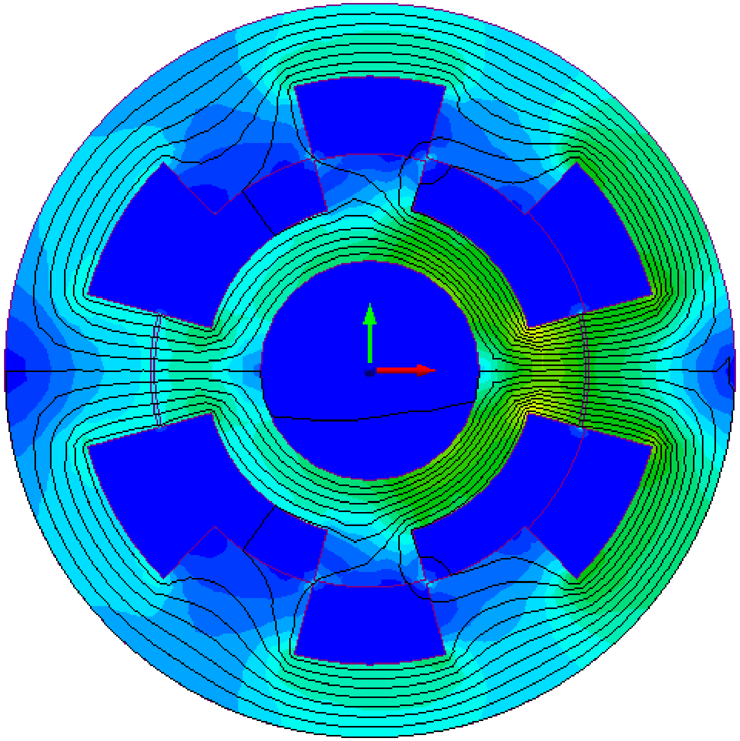
$$T_e = \frac{\pi^2}{8}\left(\frac{P_r}{P_s}\right) T_{synch} = 1.23\left(\frac{P_r}{P_s}\right) T_{synch}$$

Switched Reluctance Machines

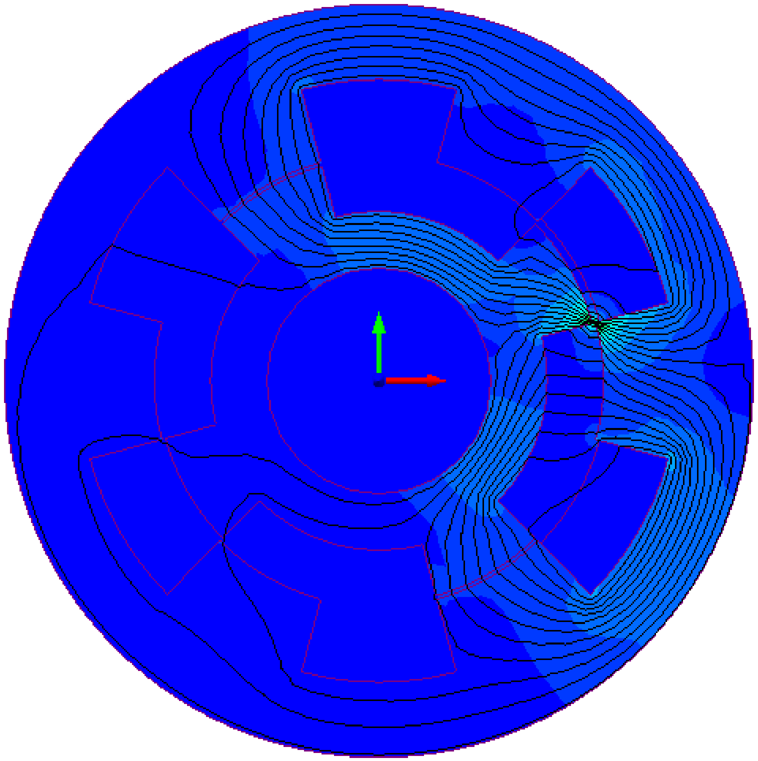


More Realistic Switching Cycle

Switched Reluctance Machines

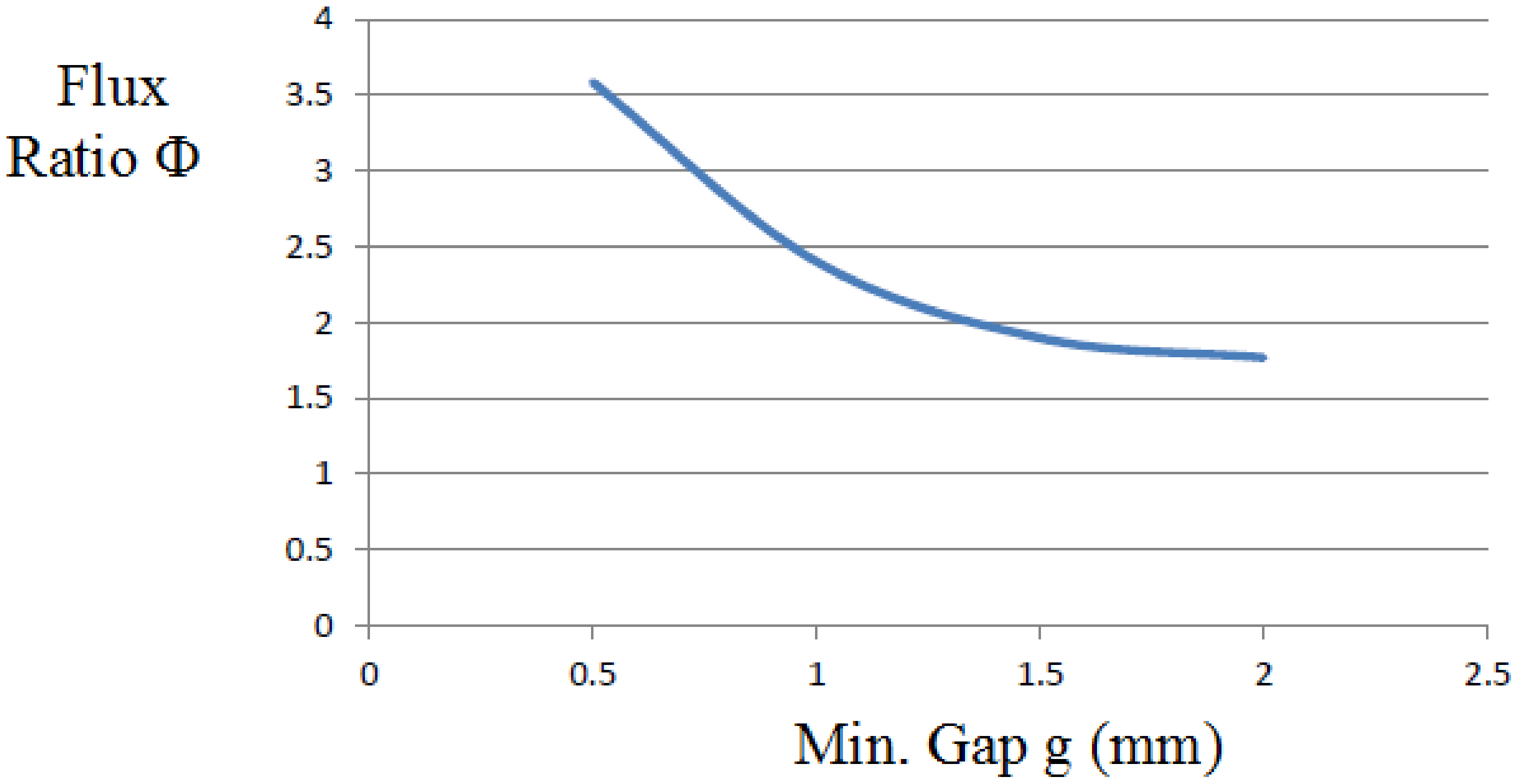


Aligned



Misaligned

Switched Reluctance Machines



Switched Reluctance Machines

$$W = W_1 - W_2 = \frac{1}{2}\lambda_1 I - \frac{1}{2}\lambda_2 I = \frac{1}{2}\lambda_1 I\left(1 - \frac{\lambda_2}{\lambda_1}\right)$$

$$\frac{W}{W_1} = \frac{\frac{1}{2}\lambda_1 I - \frac{1}{2}\lambda_2 I}{\frac{1}{2}\lambda_1 I} = 1 - \frac{\lambda_2}{\lambda_1} = 1 - \frac{\phi_2}{\phi_1} = 1 - \frac{1}{\Phi}$$

When $g = 0.5$ mm $\quad \Phi = 3.5$ and $W = 0.71 W_1$

When $g = 1.0$ mm $\quad \Phi = 2.3$ and $W = 0.56 W_1$

Switched Reluctance Machines

Hence, for idealized but realistic switched reluctance machine ($P_s = 8$, $P_r = 6$)

$$T_e = \frac{\sqrt{2}\pi}{4} B_t K_{s(rms)} D_{is}^2 L \left(\frac{W}{W_1}\right)\left(\frac{P_r}{P_s}\right)$$

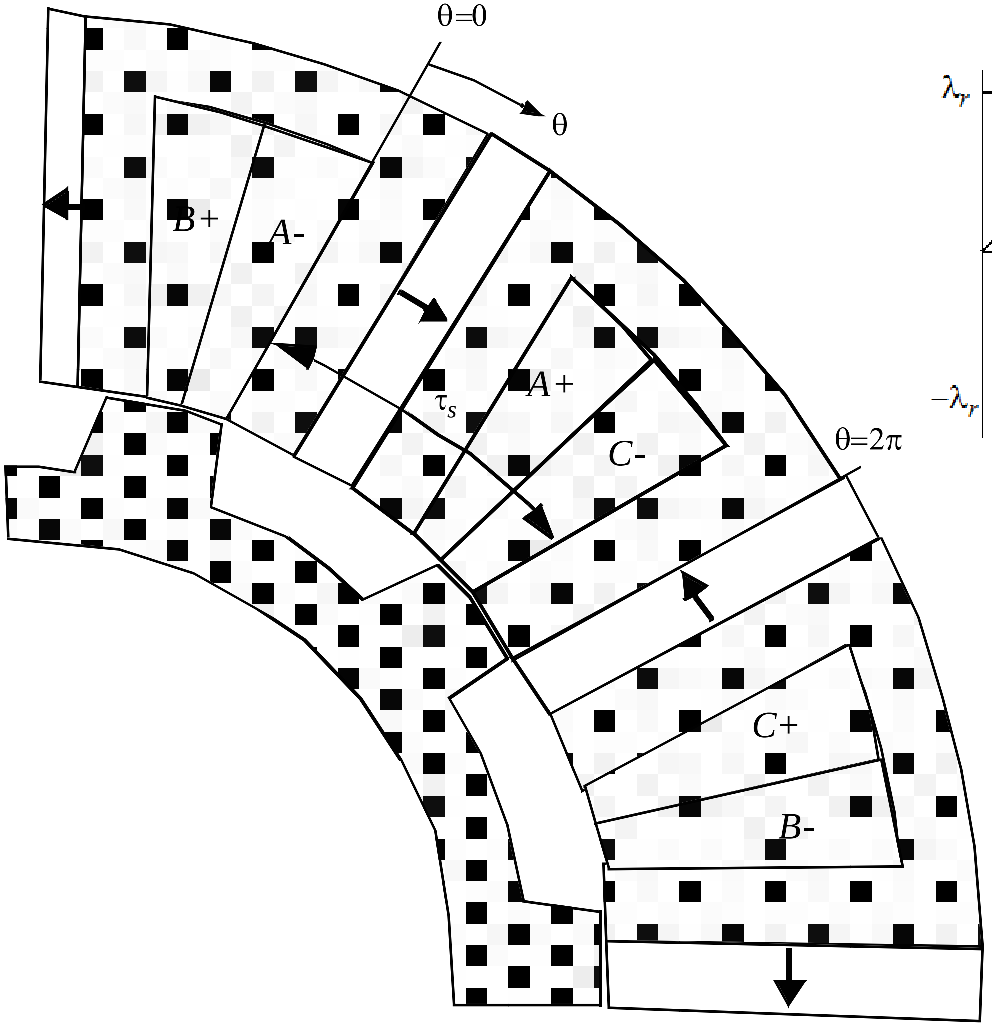
For a range of practical air gaps

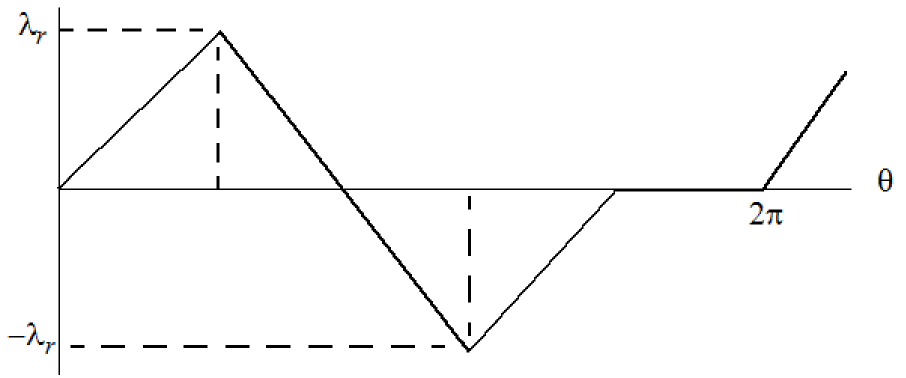
$$(0.56)(0.75)(1.28)T_{synch} < T_e < (0.71)(0.75)(1.28)T_{synch}$$

or

$$(0.538)T_{synch} < T_e < (0.682)T_{synch}$$

Switched Flux Machine





Switched Flux Machine

As the rotor moves from $\theta = 0$ to $\theta = 2\pi/5$

the flux linkage varies from 0 to

$$\lambda_t = N_c B_t A_t = N_c B_t \frac{\tau_s L}{4}$$

Thus

$$e_t = \frac{d\lambda_t}{dt} = \frac{d\lambda_t}{d\theta}\frac{d\theta}{dt} = \omega_r \frac{N_c B_t \frac{\tau_s L}{4}}{\left(\frac{1}{5}\right)\frac{2\pi}{P_r}} = \omega_r (N_c B_t)\left(\frac{5}{4}\right)\frac{P_r \tau_s L}{2\pi}$$

But $\pi D_{is} = P_s \tau_s$ in which case

$$e_t = \omega_r N_c B_t \left(\frac{5}{4}\right)\frac{P_r\left(\frac{\pi D_{is}}{P_s}\right)L}{2\pi} = \omega_r \frac{5}{4}\left(\frac{P_r}{P_s}\right) N_c B_t \frac{D_{is} L}{2}$$

Switched Flux Machine

The RMS voltage and current is

$$E_{rms} = e_t \frac{P_s}{3}\sqrt{\frac{4}{5}} = \omega_r \sqrt{\frac{5}{4}} P_r N_c B_t \frac{D_{is} L}{6}$$

$$I_{rms} = I\sqrt{\frac{4}{5}}$$

$$T_e = \frac{(3E_{rms} I_{rms})}{\omega_r} = \frac{P_r}{2} N_c B_t D_{is} L I_{phase}$$

Switched Flux Machine

$$K_{s(rms)} = \frac{P_s N_c I_{rms}}{\pi D_{is}}$$

$$T_e = \left(\frac{P_r}{2}\right) N_c B_t D_{is} L \frac{K_s \pi D_{is}}{P_s N_c} = \frac{1}{2}\left(\frac{P_r}{P_s}\right) B_t K_{s(rms)} D_{is}^2 L$$

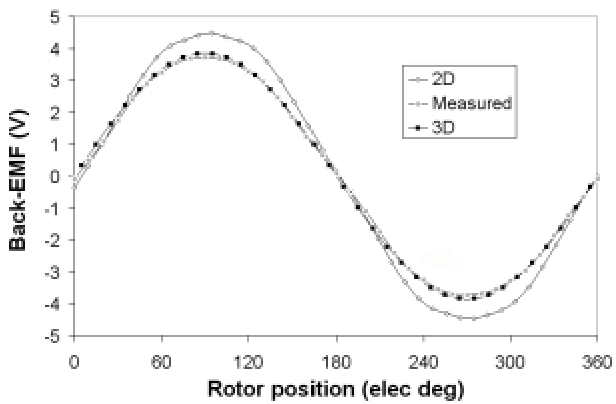
Recall

$$T_{synch} = \frac{2\sqrt{2}}{\pi} B_t K_{s(rms)} (D_{is}^2 L)$$

For a practical machine with $P_s = 12$ and $P_r = 10$, the ratio of the two torques is

$$\frac{T_e}{T_{synch}} = \frac{\left(\frac{1}{2}\right) B_t K_{s(rms)} \left(\frac{P_r}{P_s}\right) (D_{is}^2 L)}{\frac{2\sqrt{2}}{\pi} B_t K_{s(rms)} (D_{is}^2 L)} = \left(\frac{1}{2}\right)\left(\frac{\pi}{2\sqrt{2}}\right)\frac{P_r}{P_s} = 0.55\left(\frac{5}{6}\right) = 0.46$$

More Realistic Back EMF



Cause: Cancellation of Harmonics when Poles are Connected in Series

Downside: Fundamental Component Also Inevitably Reduced

Result: Effective Winding Factor of Approximately 0.9

More Realistic BEMF: $0.46(0.9) = 0.41 < \frac{T_e}{T_{snch}} < 0.46$

Switched Reluctance Machine Result

Donald Says:

Define $\tau = T_e / T_{synch}$

A Switched Reluctance Machine
Has a "Tau" Value of

$$0.538 < \tau < 0.632$$

I Therefore Consider the Switched Reluctance Machine to Be:

Switched Reluctance Machine Result

Donald Says:

A Switched Reluctance Machine
Has a “Tau” Value of

$$0.538 < \tau < 0.632$$

I Therefore Consider the Switched Reluctance Machine to Be:

A Loser!!

Switched Flux Machine Result

Donald Says:

The Switched Flux Machine
Has a “Tau” Value of

$$\tau = 0.4 \text{ to } 0.46$$

I Therefore Consider the Switched Flux Machine to Be:

Switched Flux Machine Result

Donald Says:

A Switched Flux Machine
Has a "Tau" Value of

$$\tau = 0.4 \text{ to } 0.46$$

I Therefore Consider the Switched Flux Machine to Be:

A Basket Case!

Some Features: Redeeming and Otherwise

Switched Reluctance Machine

- Phase Windings are Uncoupled (+)
- Field Weakening Relatively Easy (+)
- Stator Phases Are Concentrated Around Poles (+)
- Simple Rotor Structure (+)
- No Magnets Needed (+)
- Small Air Gap Required (-)
- 6 Switch Inverter Unconventional (-)
- Sophisticated Current Control (-)
- System Cost Advantage (?)

Some Features: Redeeming and Otherwise

Switched Flux Machine

- Simple Rotor Structure (+)
- Magnet Not Easily Demagnetized (+)
- “Sinusoidal” EMF (?)
- Complicated Stator Structure (-)
- Stator Based Magnet Takes up Valuable Space (-)
- Substantial Amount of Magnet Needed (-)
- Magnet Provides Little, If Any Benefit (-)

Looking Forward

Brushless Wound Field Synchronous Machines

Spoke Type PM Machines

Flux Reversal PM Machine

PM Assisted Reluctance Machine (PMAR)

Reluctance Assisted PM Machine (RAPM)

Optimum Use of Material

3D Structures

High Speed Machines

Low Speed Machines

High Temperature Superconducting Machines

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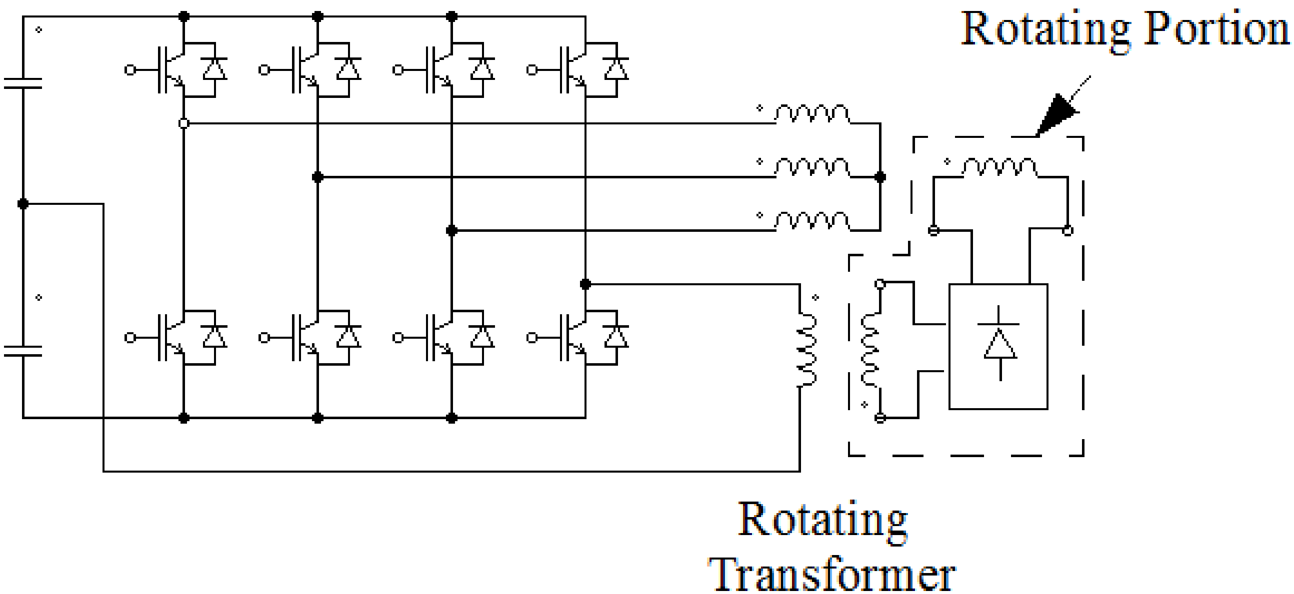
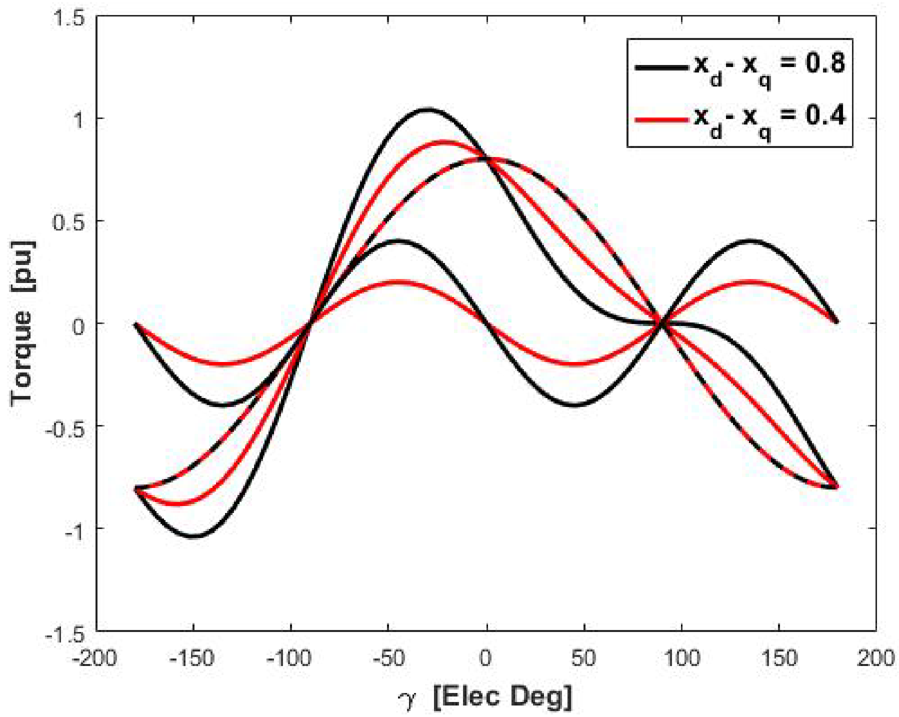


Find New Means for Brushless Excitation
Many Variations are Possible
Which is the Best? Cheapest?

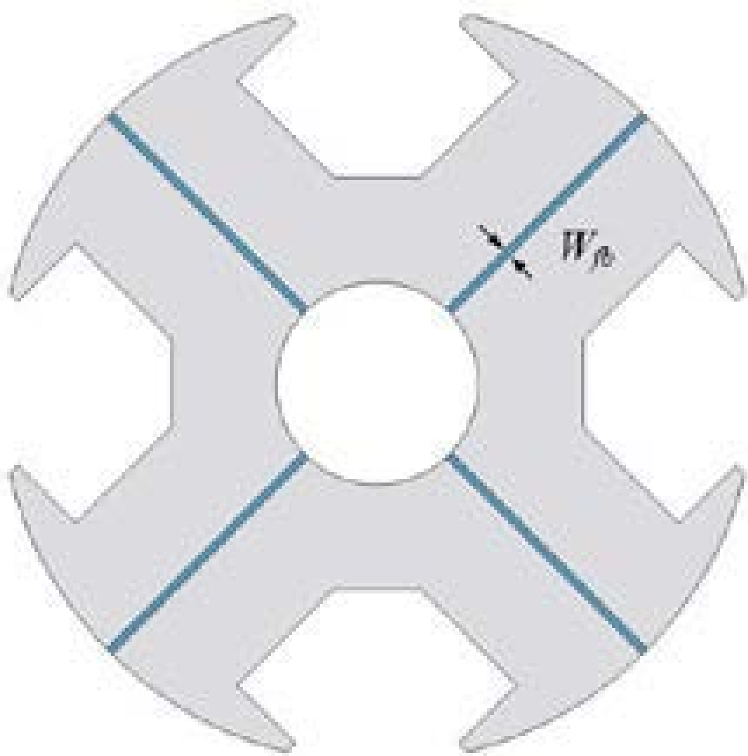
Brushless Wound Field Synchronous Machines



Constant Armature Current and Constant Field Current

Design Brushless Synchronous Machines with Increased Saliency

Brushless Wound Field Synchronous Machines



Torque Ratio τ = 1.1 Reached

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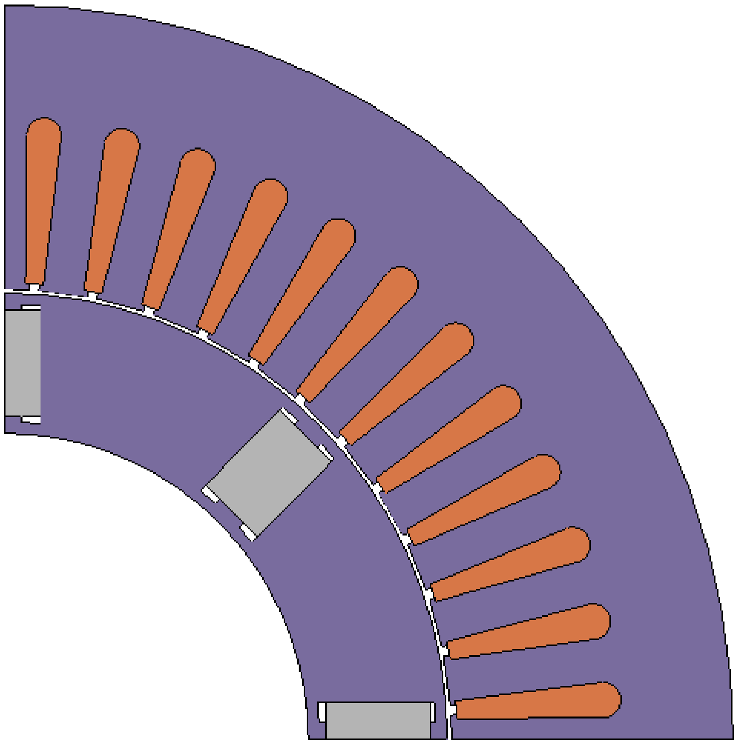

Flux Focusing Advantage Allows Use of Ferrite PMs

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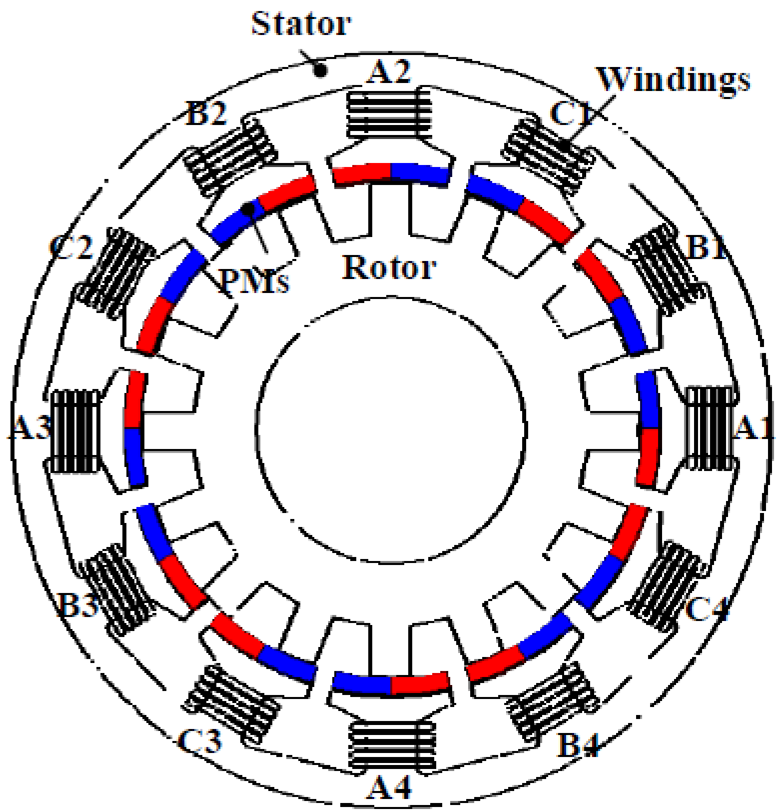

$\tau \cong 1$

Source: The flux reversal machine: a new brushless doubly salient permanent magnet machine" Deodhar, Andersson, Boldea and Miller, 1997

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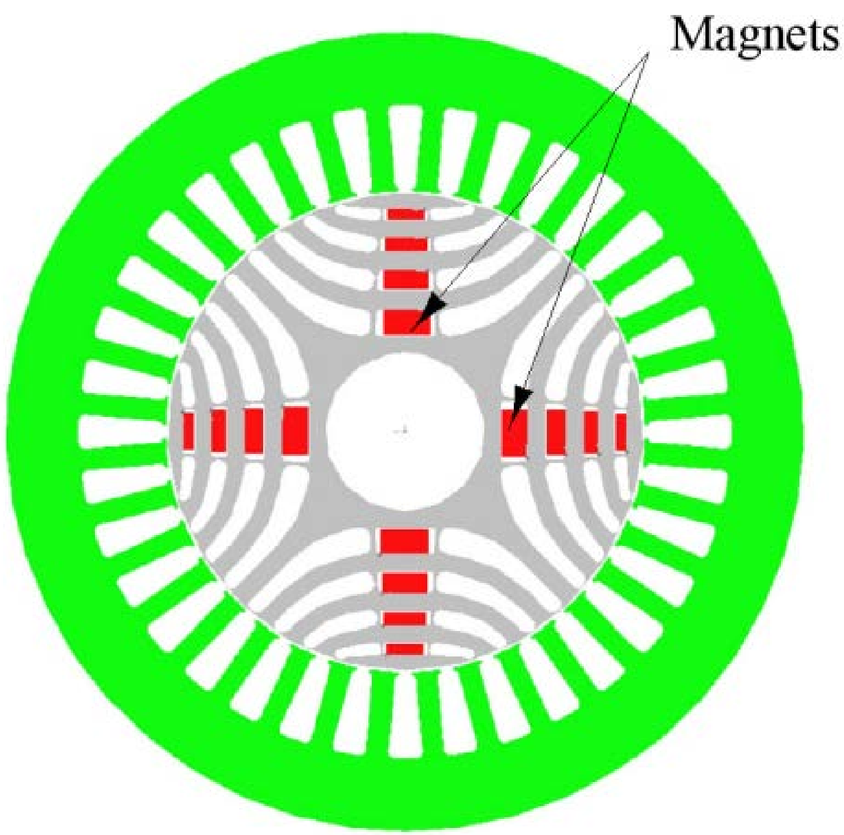

$\tau > 1$ Possible

RAPM vs PMAR: Is There a Middle Ground?

Source: P. Guglielmi, M. Pastorelli, G. Pellegrino, A. Vagati -2003

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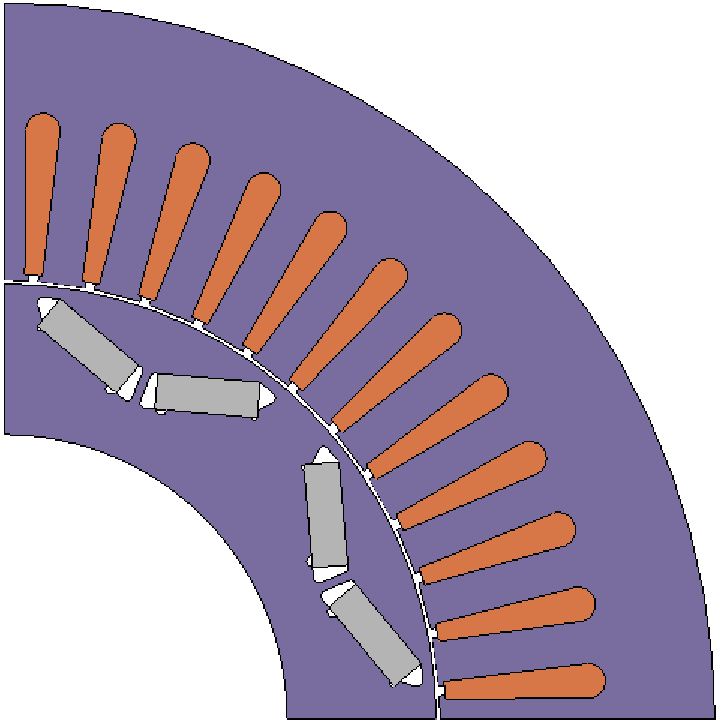

Toyota Camry Concept

1/2 PM Torque, 1/2 Reluctance Torque

Is Improvement Possible?

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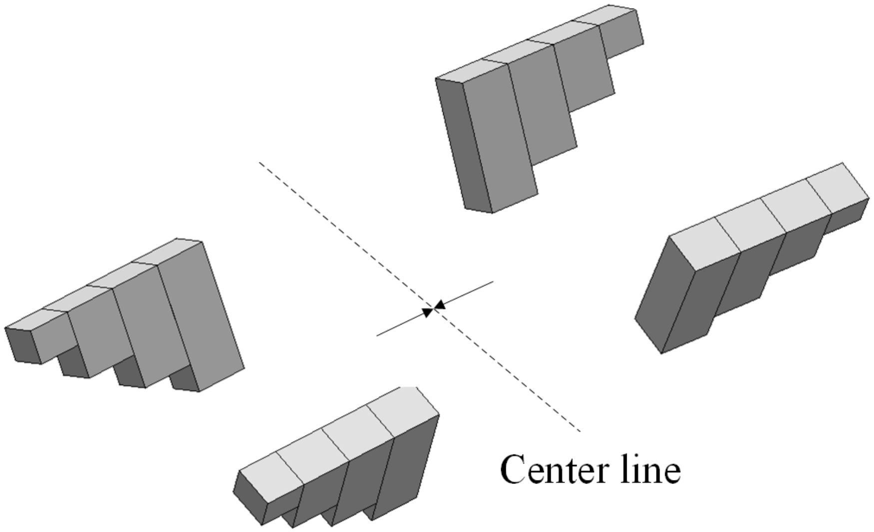
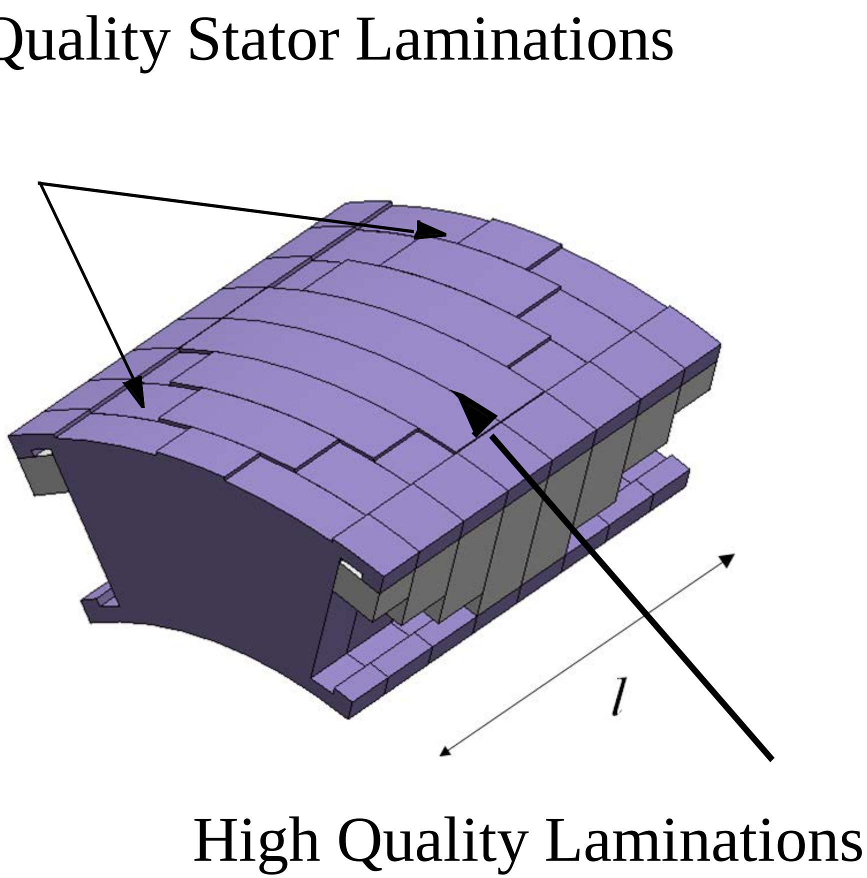
Optimum Use of Material

Example





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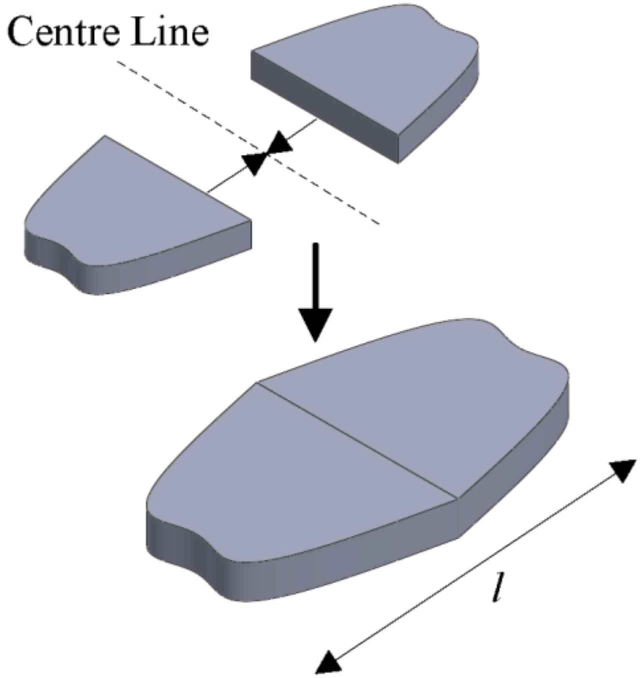

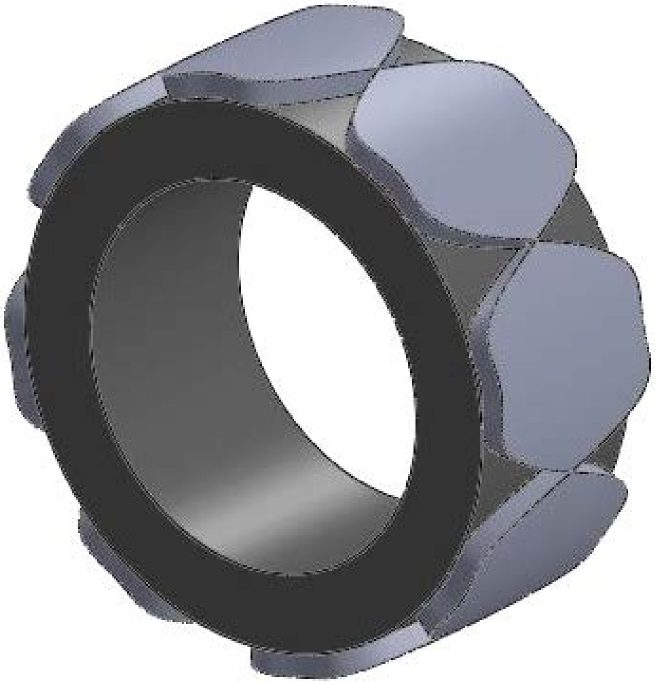

Goal: More Optimal Use of Rotor Magnets

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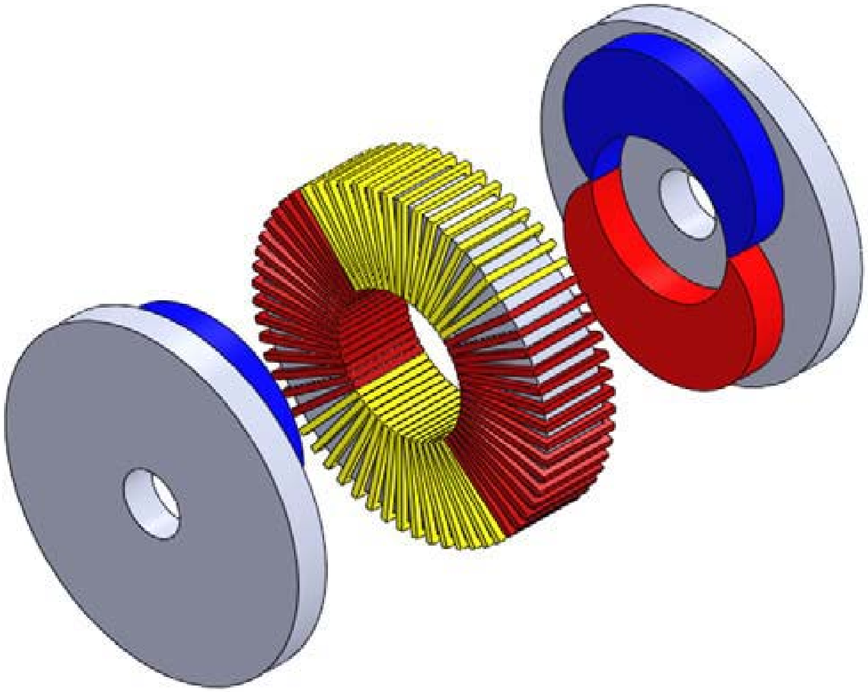

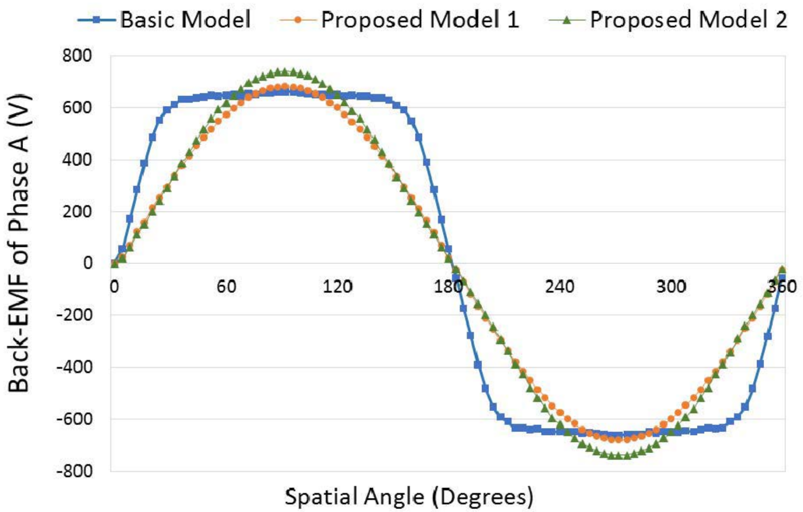

Goal: Minimal Use of Magnet, Low Torque Ripple and Losses

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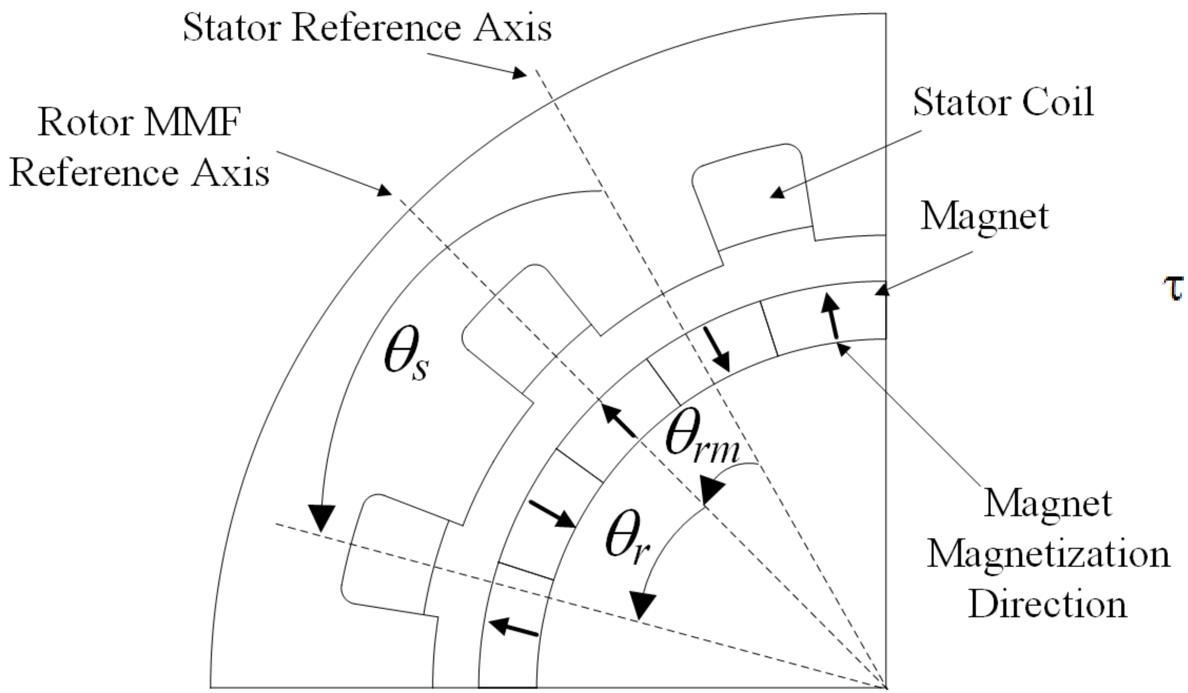

τ = 1.32 !!

Vernier Motor/Generator

- Extra torque from magnetic gear effect
- Inherent low speed machine
- Better efficiency but somewhat lower power factor

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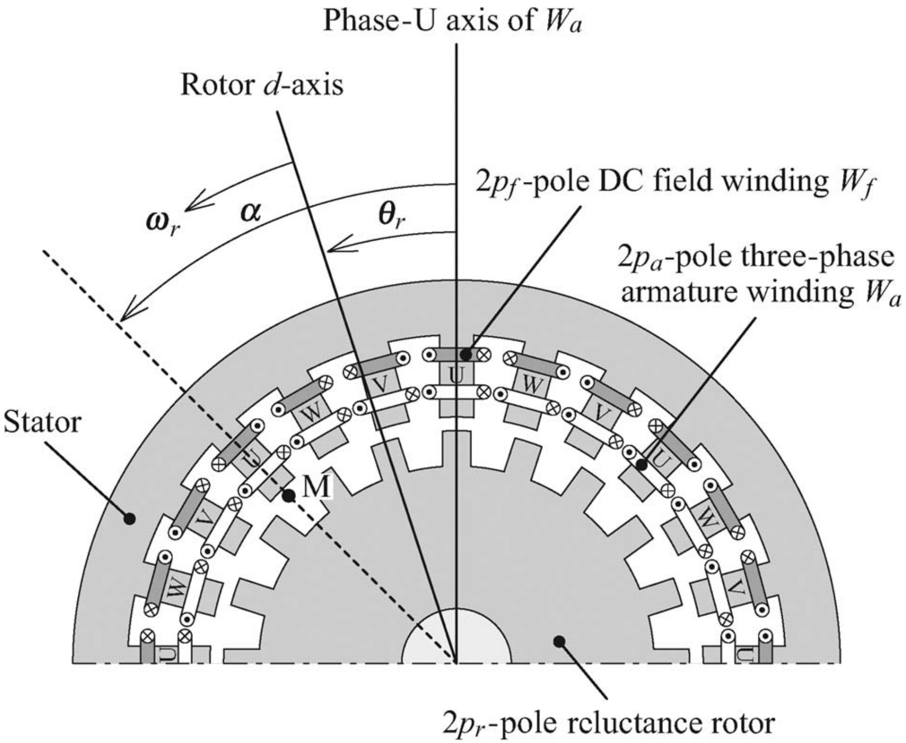

$\tau = 1.2$ Possible

- Needs Non Rotating DC Field Coil
- No Magnetizing Field Losses
- Pulsating Torque Issue

Source: Fukami, Matsuura, Shima, Momiyama, and Kawamura-2010

Summary

- Switched Reluctance Machines Are of Questionable Importance
- Switched Flux Machines Look (To Me) To Be Hopeless
- Vernier Machines Are An Attractive Possibility for the Future
- The Machines Community Sorely Needs to Establish a Common Frame of Reference to Compare Different Topologies
- Use of the “tau” Factor (Torque as a Per unit of the Torque of a Non-salient Pole Synchronous Machine) May Be a Place to Start

Thanks for Coming, Hope We're Still Friends!