Novel Permanent Magnet Brushless Machines and Applications

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Abstract :
Compared with induction machines and switched reluctance machines, one of the novel features of permanent magnet brushless machines is that there exhibit numerous machine topologies. In this presentation, selected novel topologies and performance features of various permanent magnet brushless machines will be presented and potential applications highlighted.

These include:

(a) Halbach machines,

(b) Fractional slot machines,

(c) Magnetic geared machines,

(d) Double salient and flux reversal machines,

(e) Various switched flux machines,

(f) Various hybrid excited machines, as well as

(g) Magnetless machines.

The presentation emphasis will be on some permanent magnet machines which are developed at the University of Sheffield for various applications, as well as their advantages and disadvantages. The presentation will also provide some backgrounds as to how the new concepts can be generated by utilising the novel features of machine topologies.

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Jmag User Conference 9-10 Dec. 2010

Novel Permanent Magnet Brushless Machines and Applications

Professor Z.Q. Zhu, *Fellow, IEEE*
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One of Top 10 UK Research Lead Universities

- 1905 - University of Sheffield
- 1828 - Sheffield School of Medicine
- ~24,000 students
- >3000 international students
- ~6000 staff members

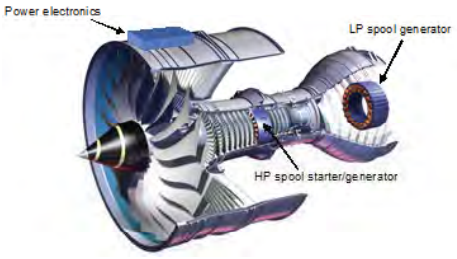
Electrical Machines and Drives Research Group

1 of 4

Main Research Groups in Dept of Elect. & Elec. Eng.
9 Academic staff and ~80 personnel in total
Headed by Prof. Z.Q. Zhu, Fellow, IEEE

Host

- Rolls-Royce University Technology Centre in "Advanced Electrical Machines & Drives"
  Director: Prof. G.W. Jewell
- Sheffield Siemens Wind Power Research Centre (S^2WP)
  Director: Prof. Z.Q. Zhu



Electrical Machines and Drives Research Group

Research activities

- PM brushless machines and control systems, and their applications
- Strong industrial collaboration, particularly in automotive, wind power and aerospace sectors
- Capability for producing and testing demonstrator systems

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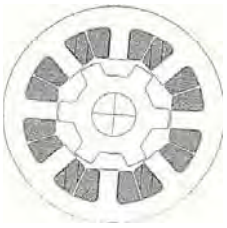
Novel Electrical Machines?

1980: Switched reluctance machine – Leeds University, UK.

P.J. Lawrenson, J.M.Stephenson, P.T.Blenkinsop, J.Corda, and N.N.Fulton, "Variable-speed switched reluctance motors," *IEE Proc.*, vol.127, no.4, pp.253-265, 1980.



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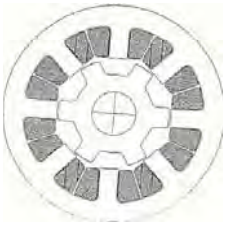

1968: Switched reluctance machine - Nasar

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Novel Electrical Machines?

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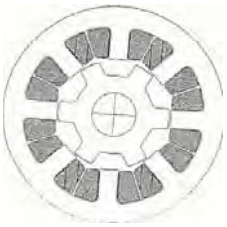
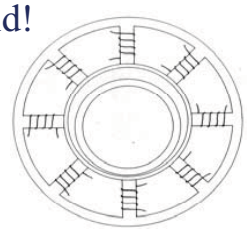


1968: Switched reluctance machine - Nasar

1841: Wheatstone's eccentric rotor motor
-the 1st electric motor in the world!



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Outline

Novel permanent magnet machines, including

- Halbach machines
- Fractional slot machines
- Magnetic geared machines
- Double salient and flux reversal machines
- Various switched flux machines
- Various hybrid excited machines
- Magnetless machines

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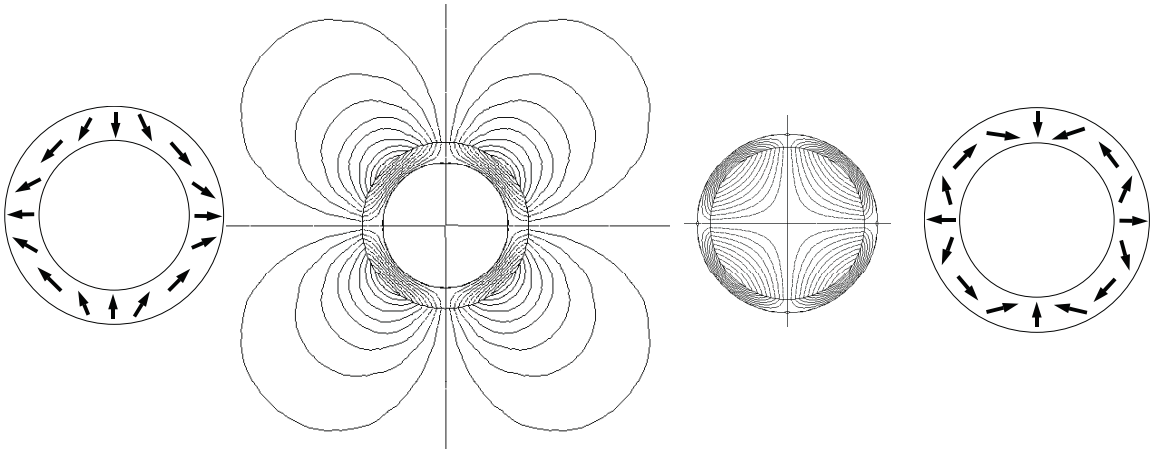
Halbach Machines

Magnet with novel magnetisation: self-shielding

- Sinusoidal & cosinusoidal circumferential & radial magnetisations



External field Internal field

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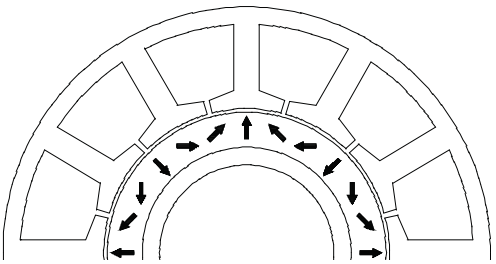
Features of Halbach Machines

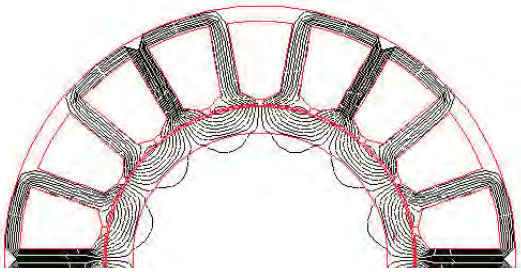
Due to self-shielding magnetisation:

- Airgap field distribution is ideally sinusoidal
  - Low stator iron loss: high efficiency & suitable for high-speed operation
  - Sinusoidal back-emf waveform: ideal for brushless ac motors
  - Negligible cogging torque: low torque ripple & low acoustic noise & vibration
- Rotor back-iron is not essential
  - Reduced rotor mass & inertia: improved dynamic performance
- Skew is not required in order to obtain sinusoidal back-emf for BLAC motor & to eliminate cogging torque
  - Low cost manufacture
- Concentrated non-overlapping stator windings can be employed
  - Short end-winding, high torque density, low copper loss & high efficiency
- A higher airgap flux density is possible
  - Appropriate for slotless machines

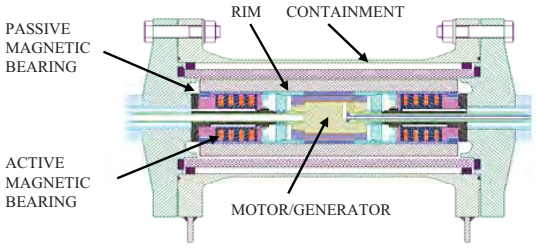
Automotive - Electric Power-Assisted Steering

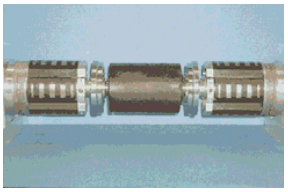
- Very low cogging torque

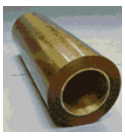




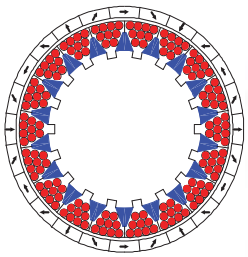
Automotive - Flywheel Motor/Generator

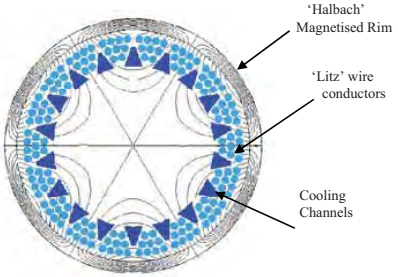






- High airgap flux density
- Ironless machine
- Low idle loss





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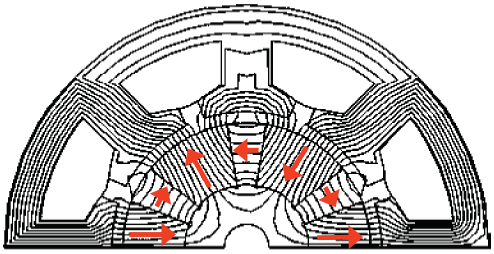
Aerospace - Fault-Tolerant Machines

- Aircraft electrical fuel pump
- Halbach magnetised fault-tolerant PM machine with a higher airgap flux density
- Large airgap can be employed for flooded rotor



- Newcastle/Goodrich

4-phase, 8-slot, 6-pole, 2 segments per pole, Halbach fault-tolerant machines

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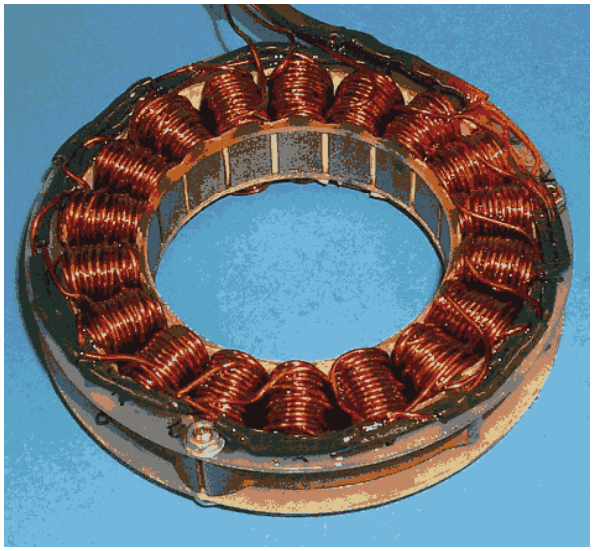
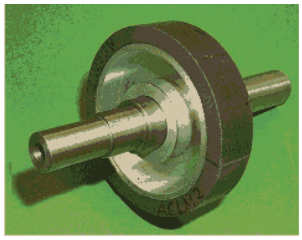
Servo Motors

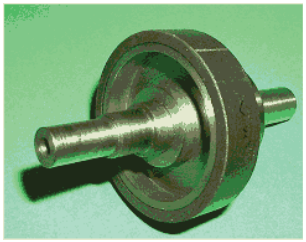


18-slot, non-overlapping, non-skewed stator



12-pole brushless motor

Air-cored Halbach rotor



Iron cored Halbach rotor

Segmented Halbach rotor

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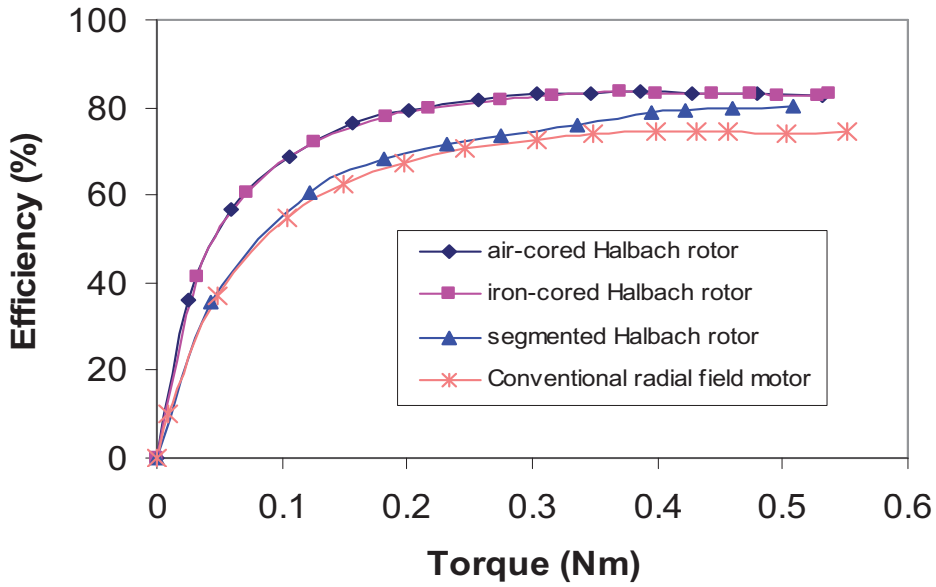
Efficiency of Alternative Servo Motors



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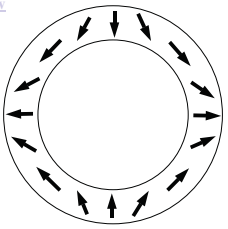
Toyota Advanced i-REAL Personal Mobility Vehicle

http://www.youtube.com/watch?v=lLB1Po5JxGI&feature=fvw



Halbach motor made by Aisin Seiki Co. Ltd. was adopted for the position control unit

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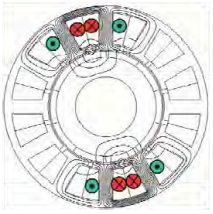
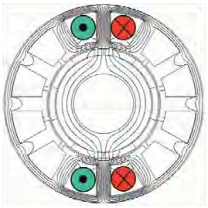
Fractional Slot PM Machine

- Number of slots per pole per phase is fractional
- Usually non-overlapping concentrated windings
- Short end-windings
- High efficiency
- High torque density
- Low cogging torque
- ….

10-pole/12-slot



Double layer



Single layer

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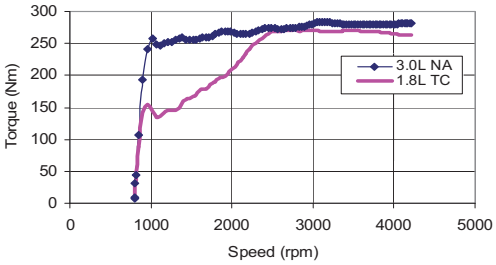
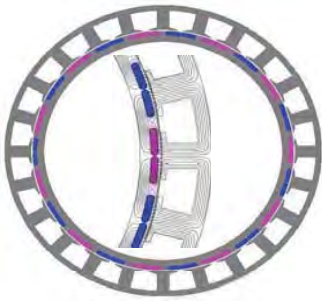
In-hub Traction Motors

- Bicycle
- EV/HEV application
- Aerospace application
- …..

Electrical Torque-Boosting of Down-Sized IC Engine

- Benefits of down-sizing
  - Reduction in fuel consumption
  - Reduced emissions
  - Lower weight
  - Comparable performance at high engine speeds
- Down-sized IC engine exhibits reduced torque at low engine speeds





3-phase, 22-poles, 24-slots, PM brushless torque-boost machine, rated output power = 18.5kW, speed =1700rpm, & torque =105Nm

Fractional Slot PM Machine

- Reduced reluctance torque, or negligible reluctance torque
- Higher mmf harmonics
- High rotor iron and magnet loss
- High noise and vibration
- Improved flux-weakening (higher winding inductance)
- Good fault-tolerant capabilities (isolated winding and per unit inductance)
- Under extensive research

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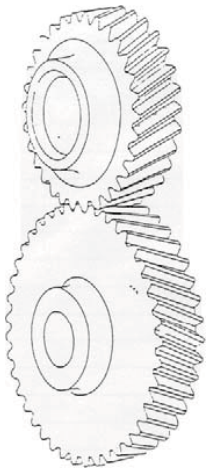
Magnetic Gear

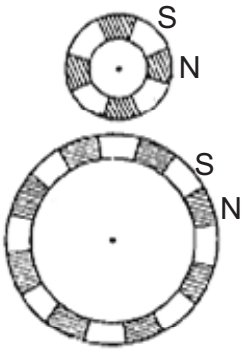
- Mechanical gear



- Single-stage helical gear

- Transmitted torque density 50 - 150 kNm/m^3
- Generally requires lubrication/cooling
- Generates noise/vibration
- Limited life

- Equivalent magnetic gear



- Poor utilisation of magnets
- Low torque transmission capability

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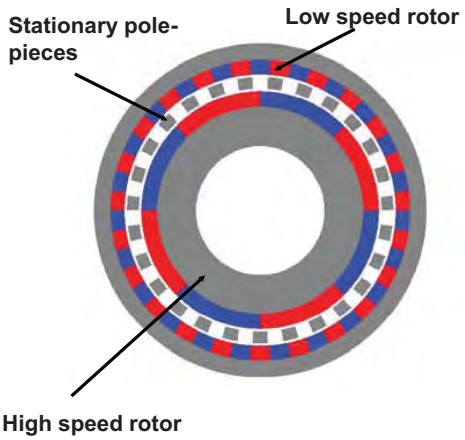
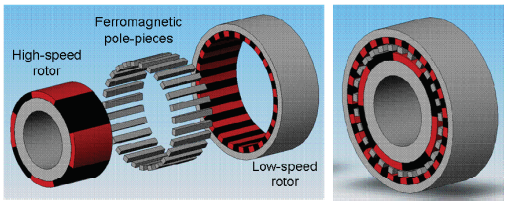
Magnetic Gear

3 components:

- 2-free to rotate, 3rd-mechanically earthed
- High speed, low pole number, PM rotor
- Low speed, high pole number, PM rotor
- Intermediate iron poles





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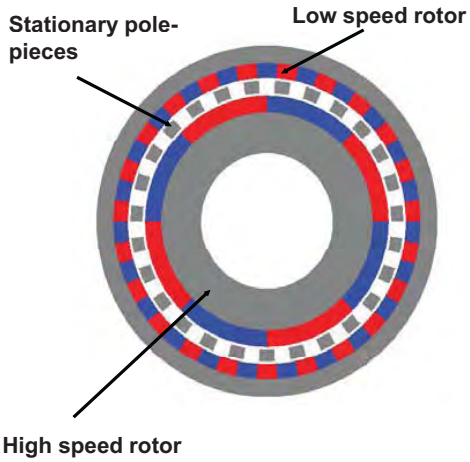
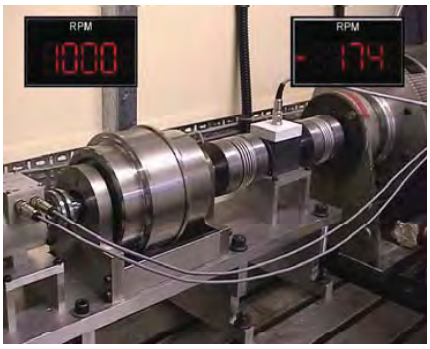
Magnetic Gear

- Zero wear and no lubrication
- Low maintenance/high reliability
- Inherent overload protection/no jamming



- Prototype 5.75:1 gear.



• Torque density: 78kNm/m^3

- Linear and axial magnetic gear formats have also been developed

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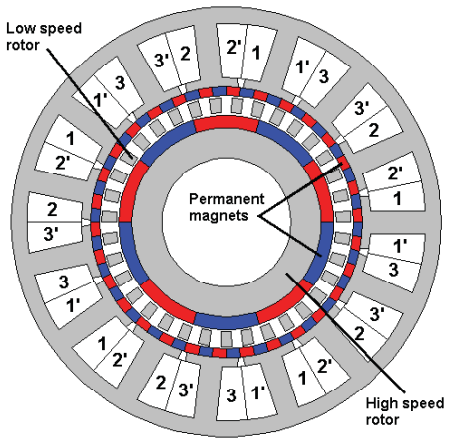
Magnetic Geared Machines



Allow to use high speed PM machines for low speed application, such as wind power generation

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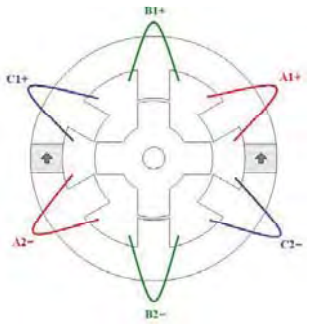
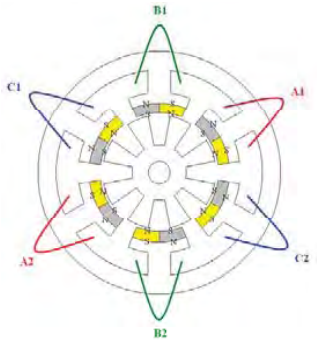
PM Machines Having PMs on Stator

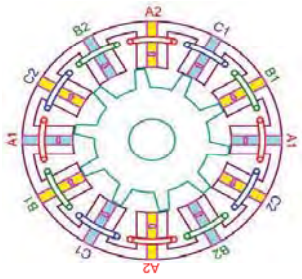
- PM on stator
- Salient pole stator with non-overlapping, concentrated stator winding
- Salient pole rotor without winding and magnet
- Reluctance action
- Negligible reluctance torque



Doubly salient



Flux reversal



Switched flux

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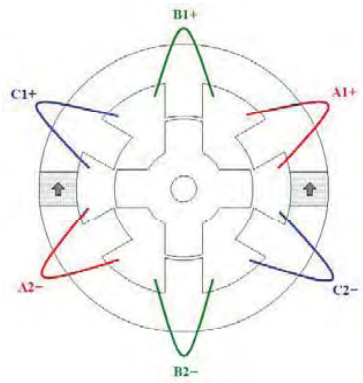
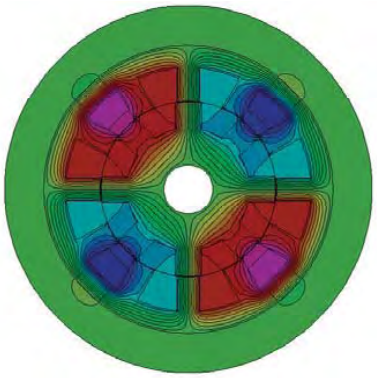
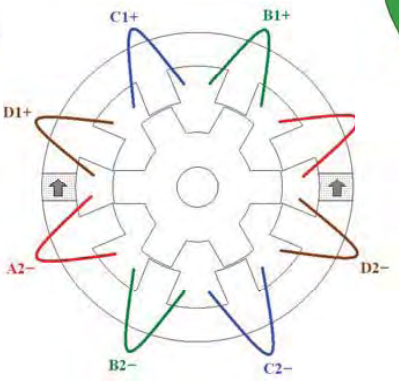
PMs at Stator Back-iron - Doubly-salient PM Machines



3-phase

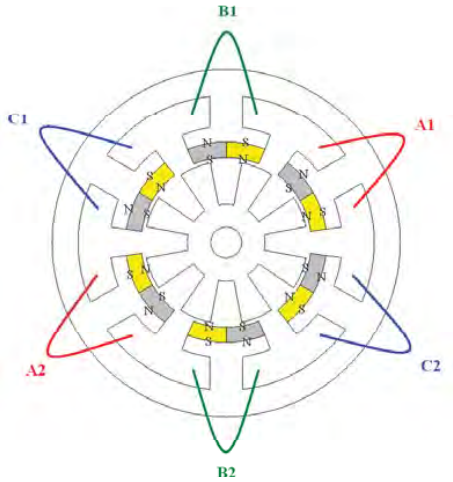


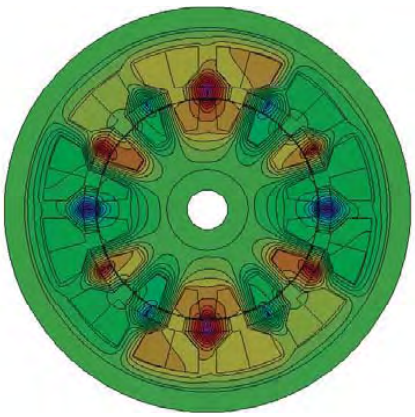


4-phase

- Circumferentially magnetized magnets placed alternatively every 3- or 4-phase stator poles
- Unipolar flux-linkage
- Low torque density

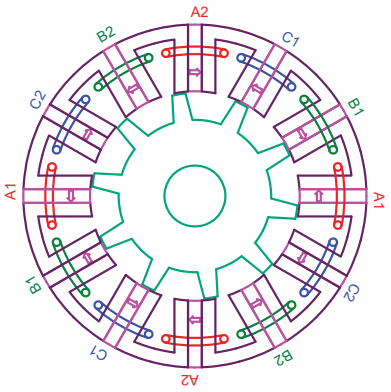
PMs on Stator Tooth Surface - Flux-reversal PM Machines

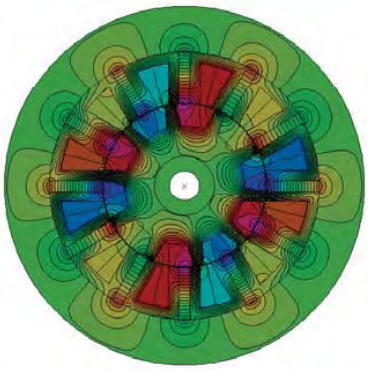




- A pair of N- and S-pole magnets placed on surface of each stator tooth
- Bipolar flux
- Low magnetic loading
- Low torque density

PMs between Stator Teeth - Switched Flux PM Machines





- Magnets between each pair of stator teeth
- Flux-focusing
- Bipolar flux-linkage
- High torque/power density
- Sinusoidal phase back-emf, ideal for brushless AC operation

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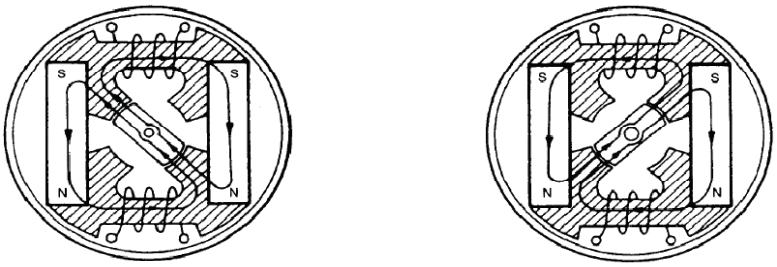
Development of Switched Flux PM Machine

1-phase switched flux PM (SFPM) brushless machine (1955)



(a) (b)

Main flux is reversed when rotor rotates one stator pole pitch, i.e. from (a) to (b).

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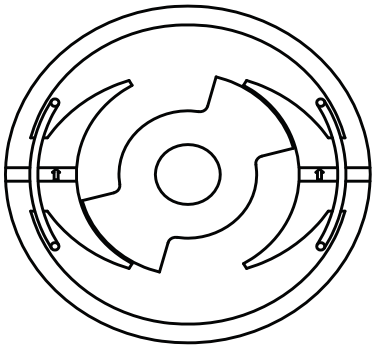
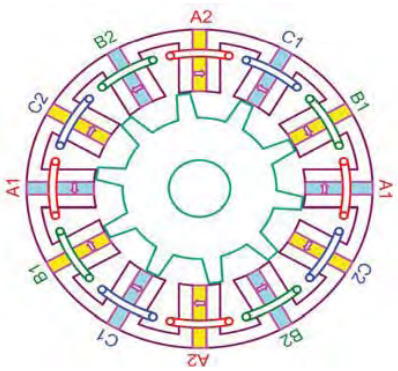
SFPM Machine Topologies

1-phase



- Low cost application
- Limited angle: actuator
  – Laws relay

3-phase



- Smooth torque
- 3-ph, 12/10 stator/rotor pole (1997)

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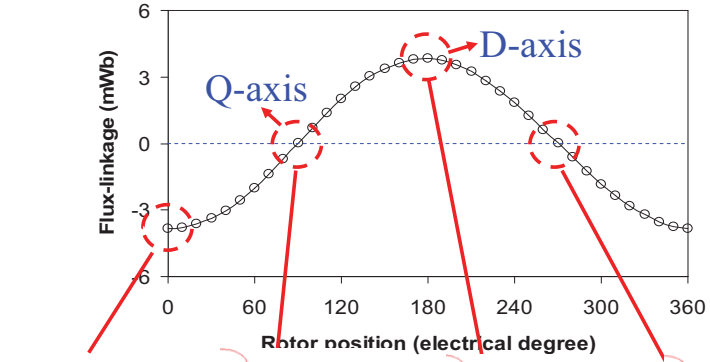
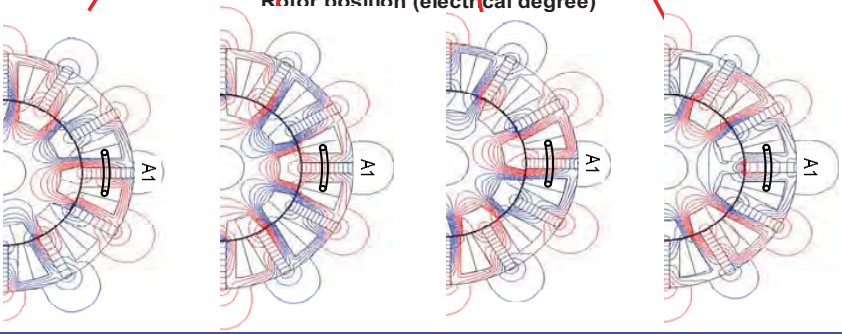
Operation Principle of SFPM Machine





- When rotor pole aligns with one side stator tooth
  – negative max flux linkage
- When rotor pole aligns with another side stator tooth
  – positive max flux linkage
- When rotor pole/slot aligns with magnet
  – zero flux linkage

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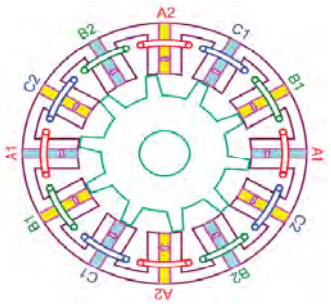
Advantages and Disadvantages of SFPM Machine

Advantages

- Simple and robust rotor
- Suitable for high speed operation
- Easier to manage magnet temperature rise
- Flux focusing / low cost ferrite magnets may be used
- Modular stator
- Sinusoidal back-emf waveform – suitable for brushless AC operation
- Fractional slot – low cogging torque

Disadvantages

- Reduced copper area
- Low over-load capability due to heavy saturation
- Complicated stator
- Leakage outside stator
- High magnet volume



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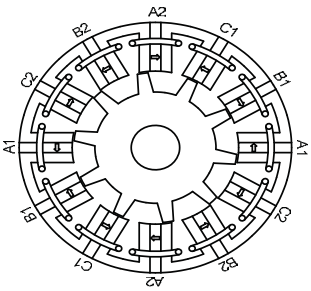
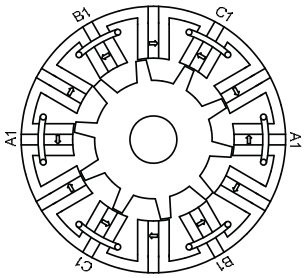
Alternative Advanced SFPM Machines

Conventional 3-phase SFPM machine, 12/10

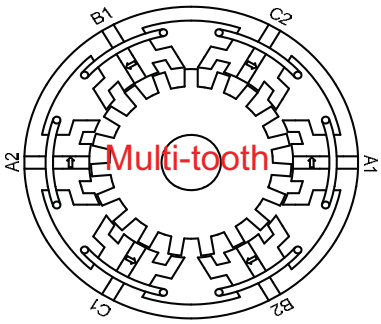
Reduction of magnet usage:
no of magnet halved
but torque is increased

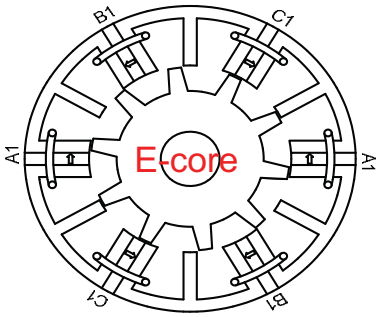


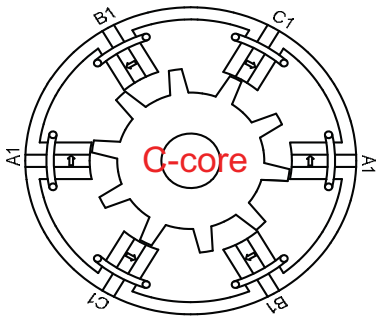
All poles wound



Alternate poles wound







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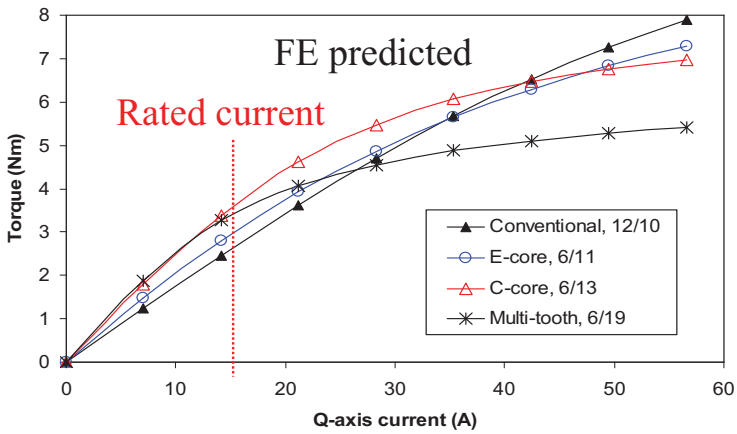
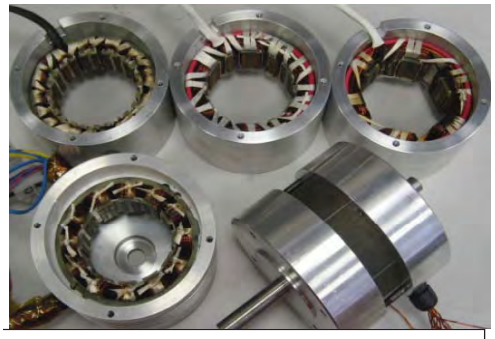
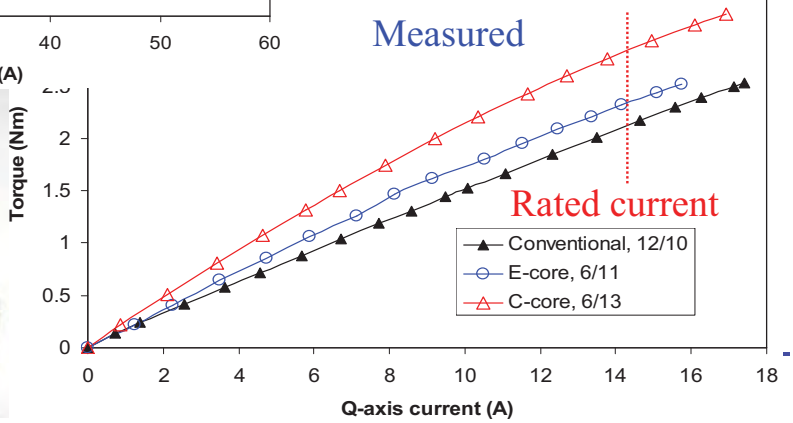
Torque Capability of Alternate SFPM Machines







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Variable Flux PM Machines

Rare earth PM machines

Advantages:

- High torque density
- High efficiency

Disadvantages:

- Expensive magnet and limited resources
- Not adjustable flux

→ Variable flux – hybrid PM and coil excitation

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Various Variable Flux PM Machines

Means for varying flux:

- Mechanical
- Electric

Excitation flux path topology:

- Series
- Parallel

Coil excitation location:

- Stator
- Rotor

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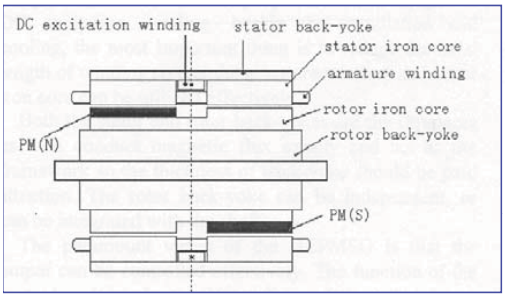
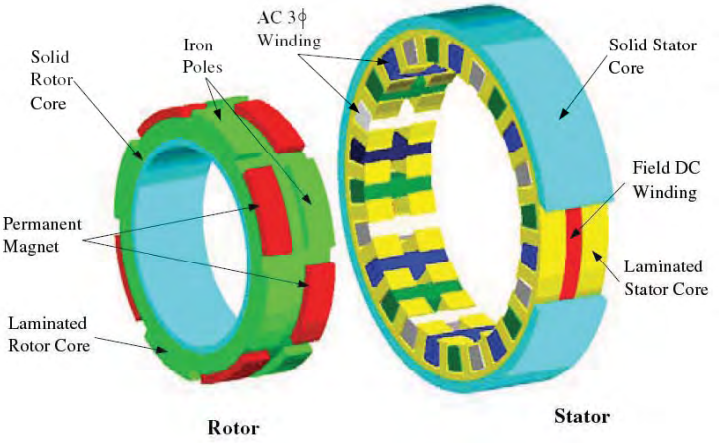
Hybrid PM and Coil Excited Machines

Based on consequent-pole PMM





E. Spooner, et al 1989; Sugii, et al 1996; J. A. Tapia, et al 2001

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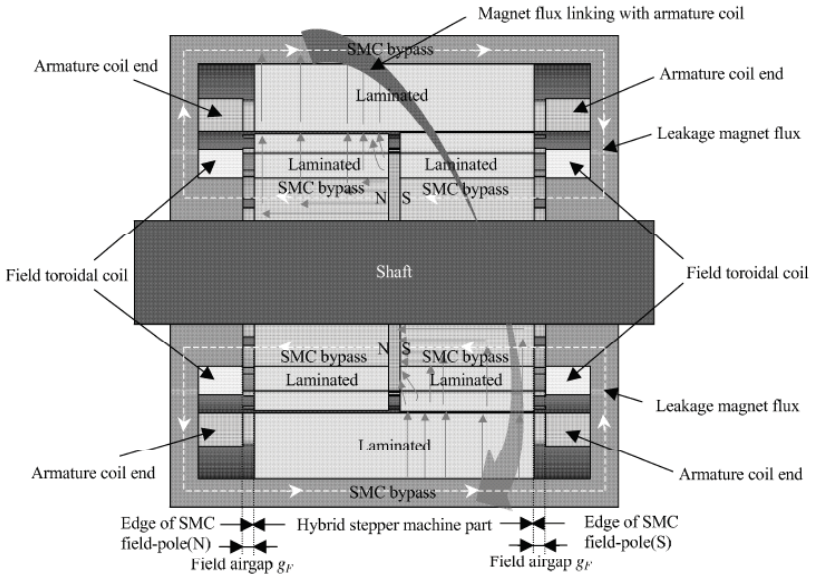
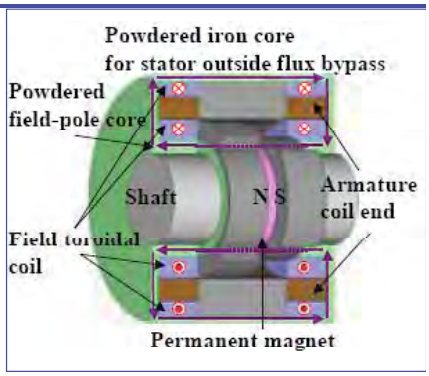
Hybrid PM and Coil Excited Machines

Based on hybrid stepper PMM





T. Kosaka, et al 2005

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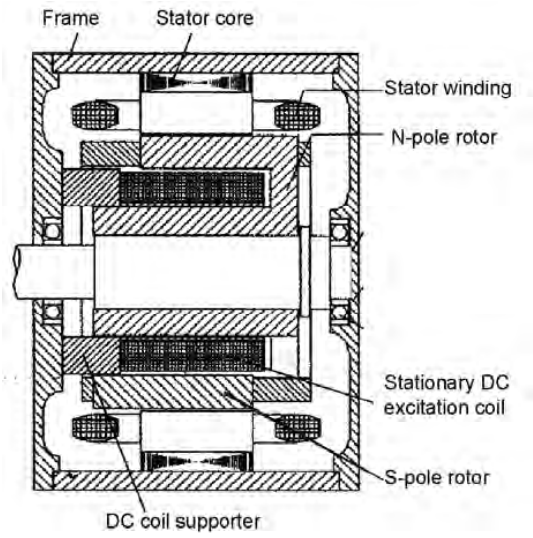
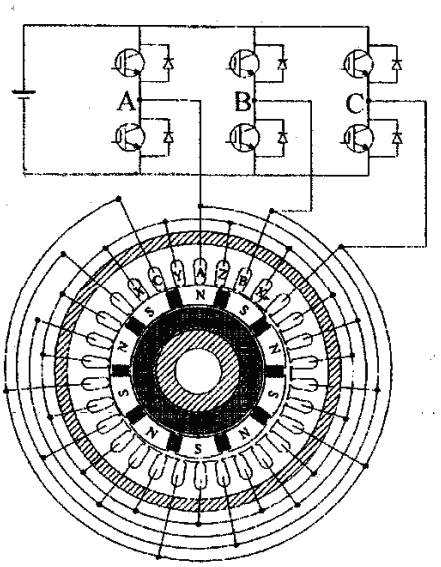
Hybrid PM and Coil Excited Machines

Based on claw-pole PMM





C.C. Chan, et al 1996

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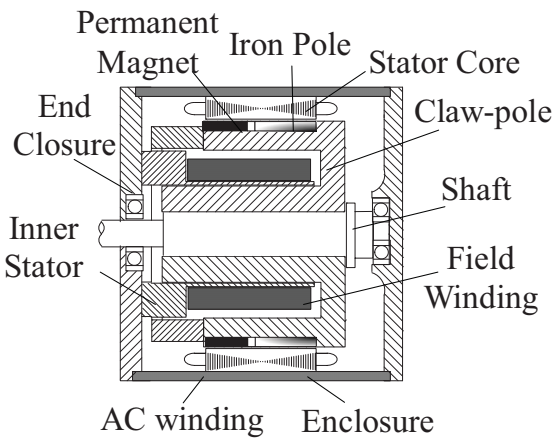
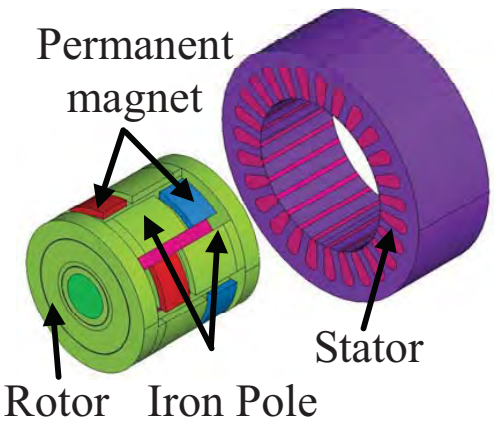
Hybrid PM and Coil Excited Machines

Based on claw-pole PMM





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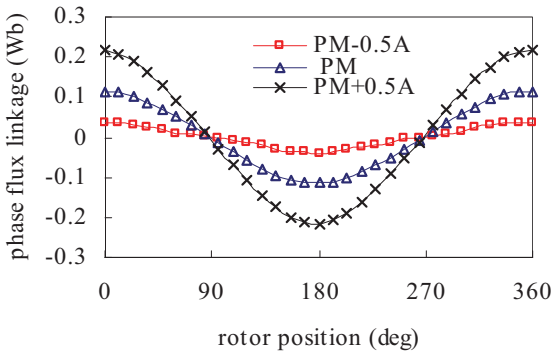
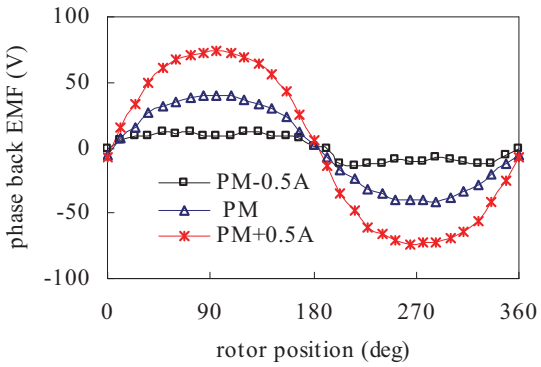
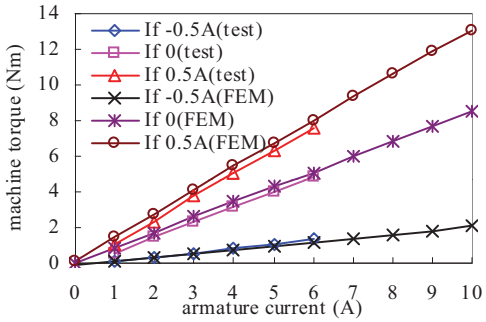
Hybrid PM and Coil Excited Machines







Hybrid excitation based on claw-pole PMM

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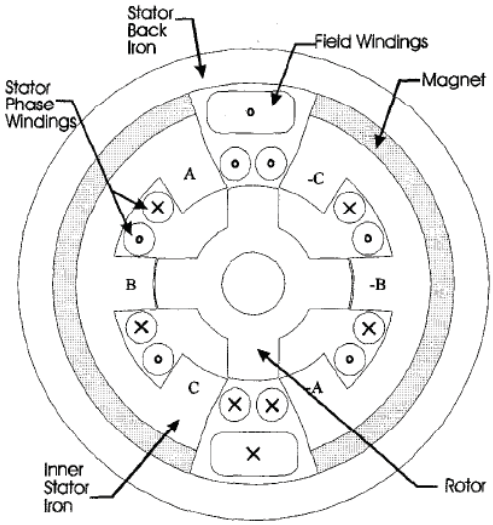
Hybrid PM and Coil Excited Machines

Based on doubly-salient PMM

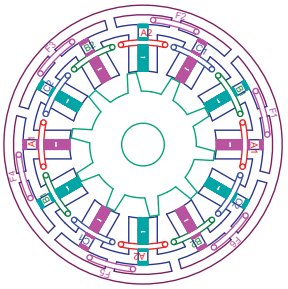


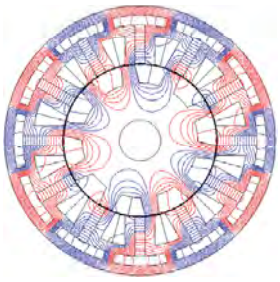
- Series excitation
- Low torque density

F. Leonardi, et al 1996

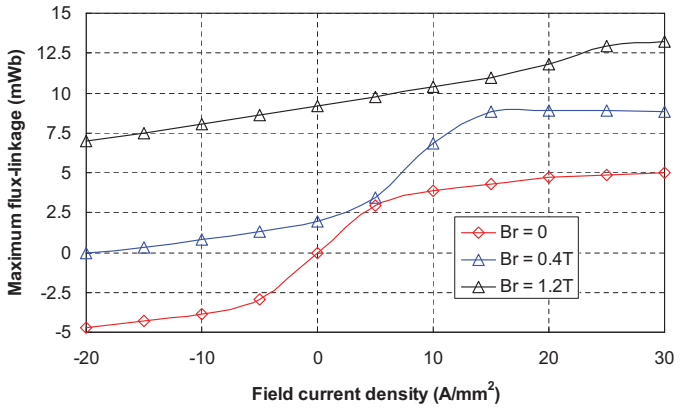
Hybrid PM and Coil Excited Machines

Based on switched flux PMM





- Parallel excitation
- Low torque density



E. Hoang, et al 2007

Hybrid PM and Coil Excited Machines

Advantages:

- Easy to achieve constant power operation (flux weakening)
- Potentially enhanced low speed torque
- Reduced risk of high open-circuit back-emf at high speed during flux weakening
- High efficiency operation possible

Disadvantages:

- Complicated structure
- Torque capability likely reduced
- Limited flux enhancing capability due to magnetic saturation
- Extra DC source required, or
- Extra mechanical means required

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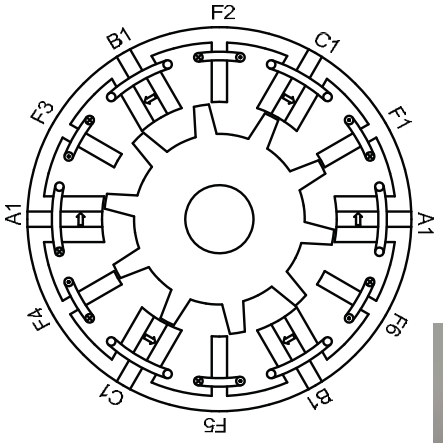
A Novel Hybrid PM and Coil Excited Machines

Based on SFPM machine



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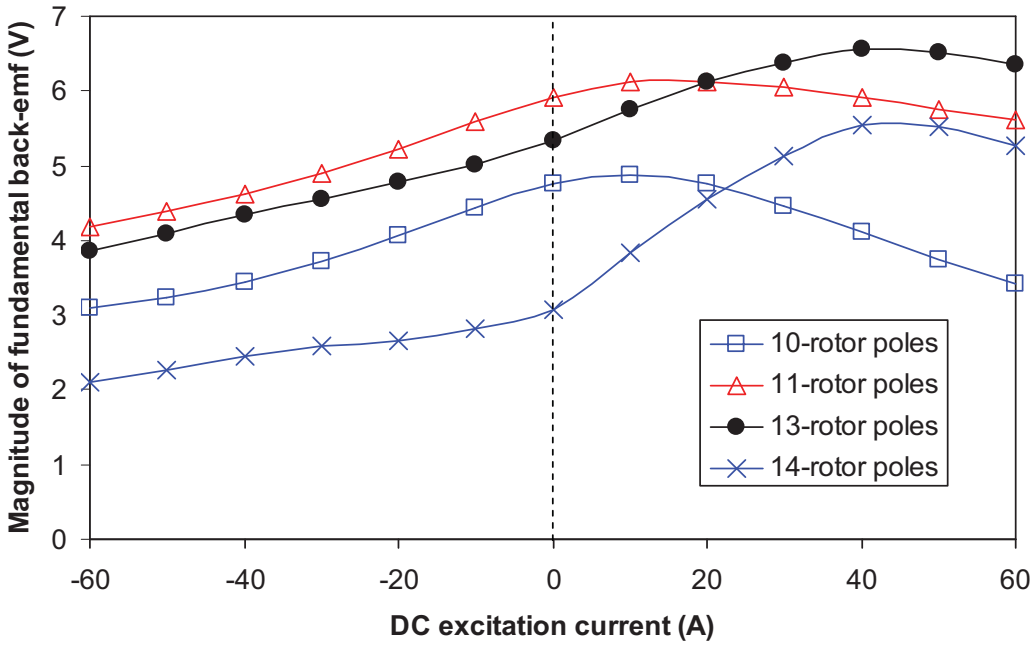
A Novel Hybrid PM and Coil Excited Machines



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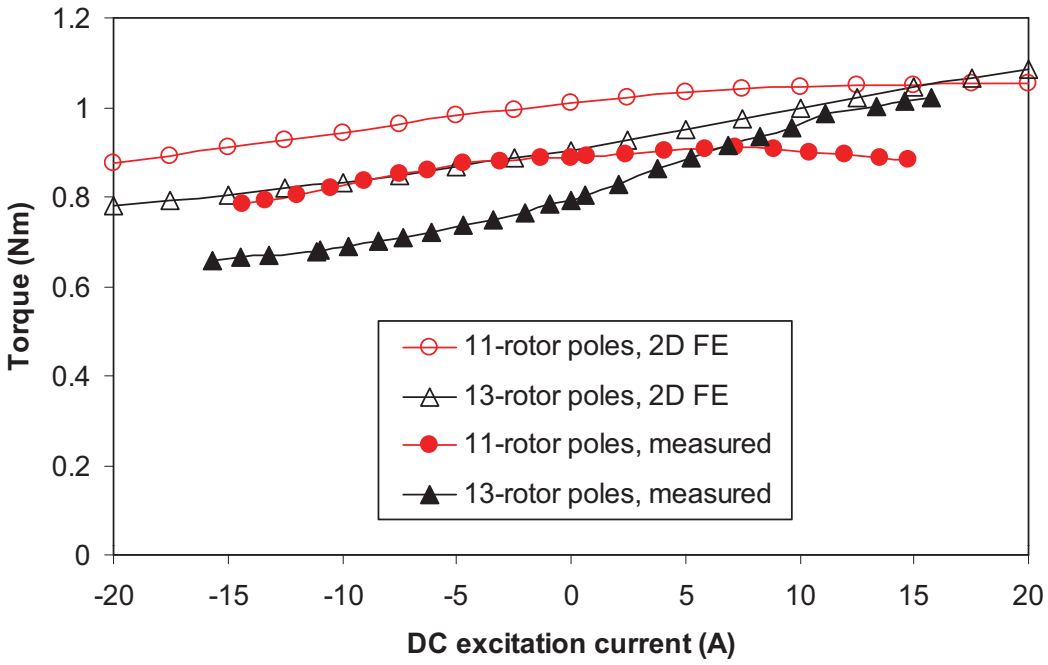
A Novel Hybrid PM and Coil Excited Machines



Magnetless Machines

Permanent magnet machines

- Limited resource: only to a few countries
- Expensive
- Potential irreversible demagnetisation
- Not easy to adjust the flux

→ Magnetless machines!

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Magnetless Machines

Claw-pole machines

- High leakage and eddy current loss
- Low power and power density

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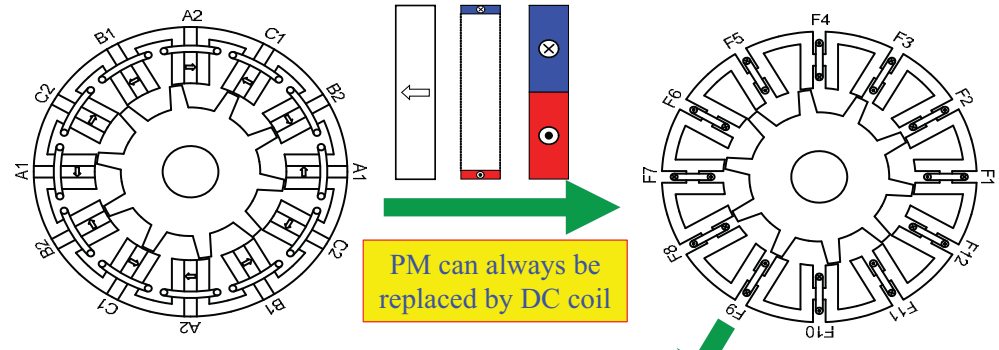
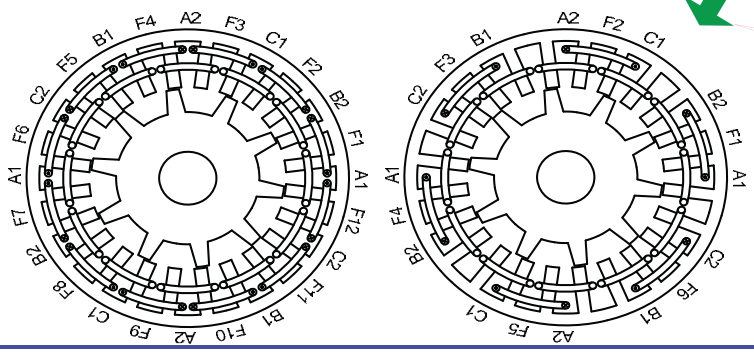
Magnetless Machines





DC field conductors close to outer stator surface can be removed

3-phase DC excited switched-flux machines

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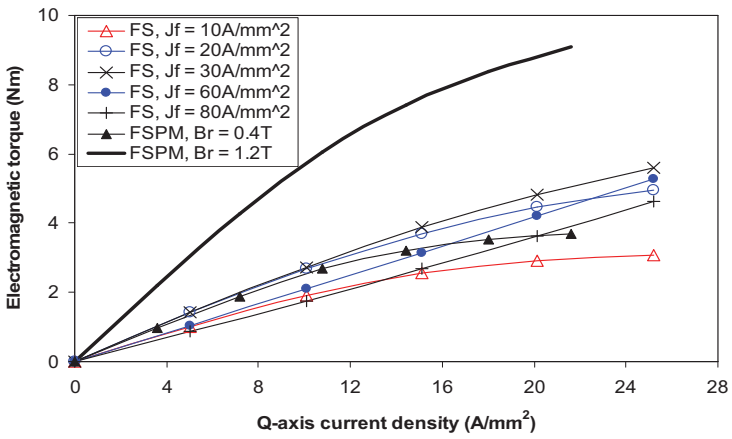
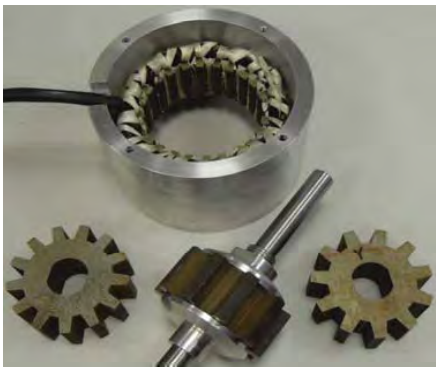
Comparison of Torque with SFPM Machine



PM machine exhibits high torque density



DC excited SF machine produces

- similar torque to Ferrite magnet SFPM machine,
- significantly lower than NdFeB magnet SFPM machine

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Magnetless Machines

Wound field excited synchronous machines:

- Slip ring/brush required
- Lower torque/power density
- Lower efficiency
- It may become attractive since the reduction in torque/power density and efficiency become less when the machine power is high

Direct-drive wind power electrically excited synchronous machine

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Magnetless Machines

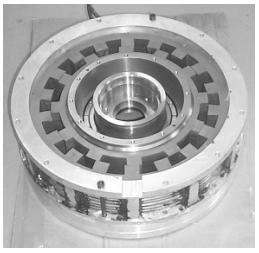
Switched reluctance machines:

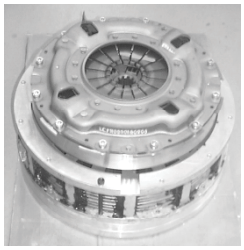
- Simple rotor
- High torque ripple and acoustic noise

Induction machines:

- Mature technology
- Excellent flux-weakening performance

Traditional magnetless machines are high torque density machines and should be reviewed !





SR machine with integrated flywheel and clutch for mild-hybrid vehicle. Cranking: 45Nm (0-300rpm), continuous motoring: 200Nm (300-1000rpm), transient motoring: 20kW (1000-2500rpm), continuous generating: 15kW (600-2500rpm), transient generating: 25kW (800-2500rpm).

120 Nm, 11.5kW at maximum speed of 7600 rpm, 26kW at base-speed of 2020rpm

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Summary

- Numerous PM machine topologies
- Each may exhibit some novel features but also problems
- No “perfect” PM machine
- Advantages depend on application/requirement
- PM machines exhibit high torque density and high efficiency
- New PM machine topologies still emerging
- Traditional “old” machine topologies should be re-examined for new application/requirement

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Thank you!