ULTRA-HIGH SPEED MACHINES

EE 564

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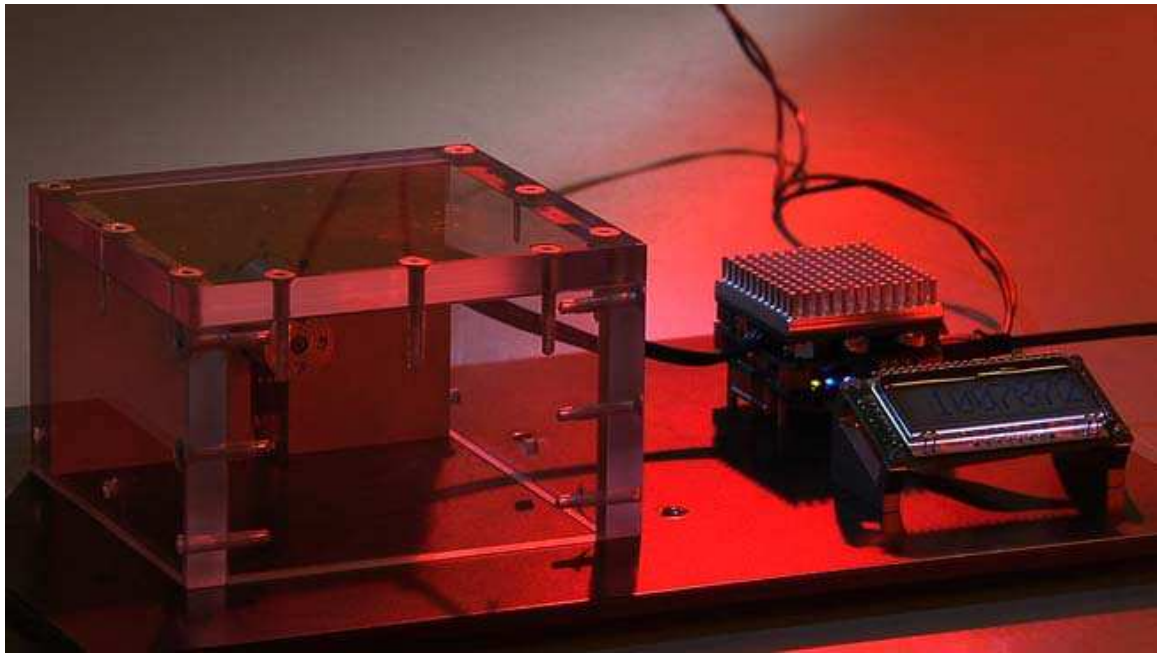
The Record

- 1,007,872 rpm at 100 W
- Manufactured by ATE GmbH, and developed by ETH Zurich Department of Power Electronics
- Titanium shell to withstand «flying apart like a star»



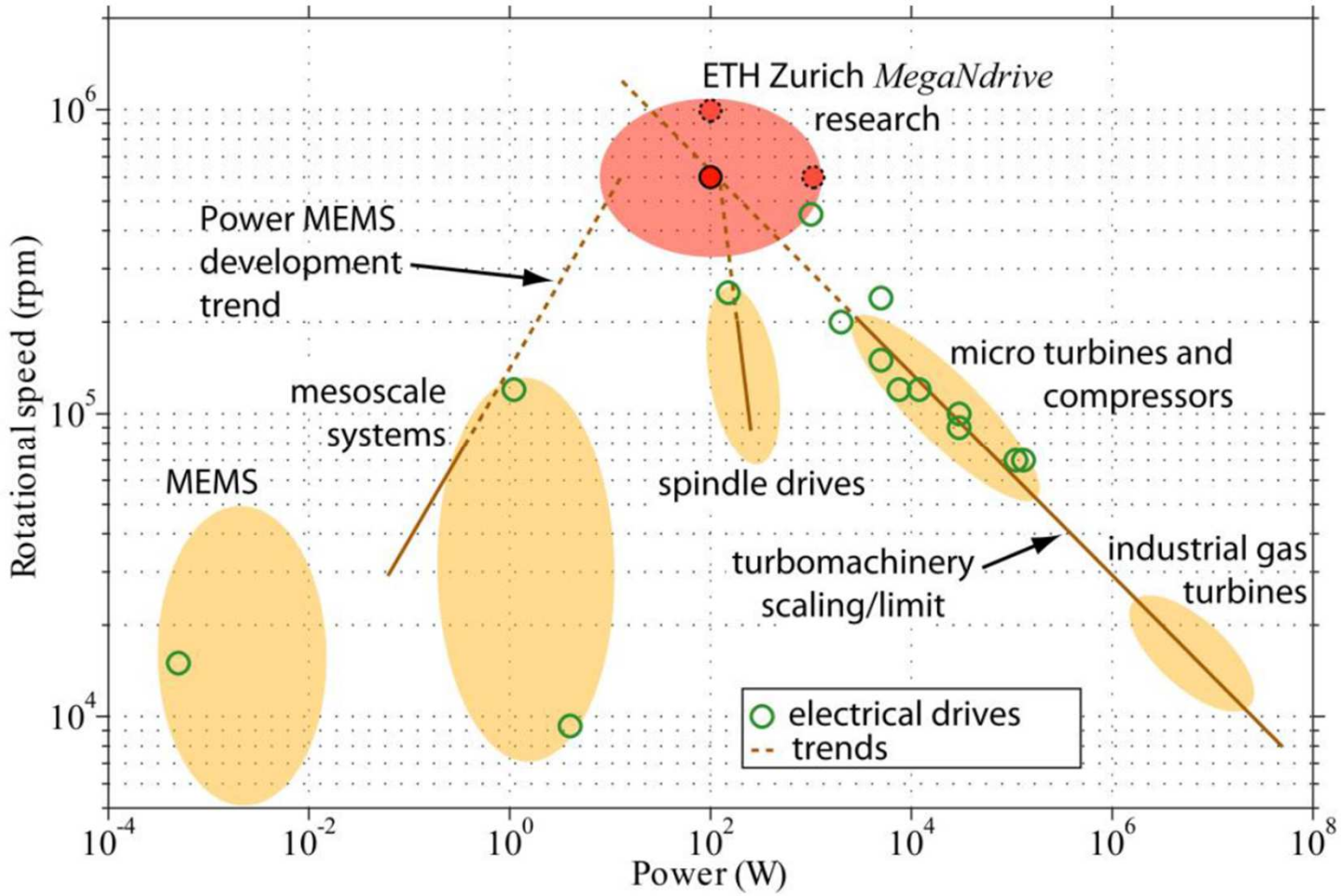
Outline

- Introduction
- History
- Working Principles
- Advantages
- Challenges
- Application Areas
- Conclusion
- References

Introduction

- Continous need for increased power density
- Increasing the rated speed to boost power density and efficiency
- Higher performance in smaller volume
- Low mass, compact design for various applications

Introduction



Emerging application areas and trends

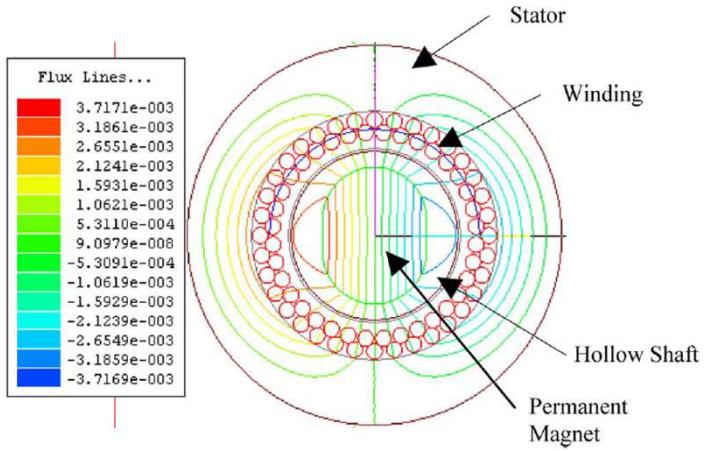
History

- Driven by cutting technology
- Carl J. Salomon and Krupp AG filed patents for high speed cutting methods in 1931
- Graham, 1993: 20,000 rpm 2 MW IM
- Soong, 2000: 47,000 rpm 21 kW laminated rotor IM
- Aglen, 2003: 70,000 rpm 110 kW MT rotating PM generator
- Mekhiche, 1999: 92,500 rpm 45 kW IM
- Jokinen, 1997: 100,000 rpm 62 kW coated solid-rotor IM
- Zhao et al, 2007: 200,000 rpm 2 kW PM synchronous motor
- Zwyssig et al, 2007: 500,000 rpm 1 kW slotless PM machine
- Suttles et al, 2014: 750,000 rpm SR motor
- Zwyssig et al, 2008: 1,000,000 rpm 100 W motor

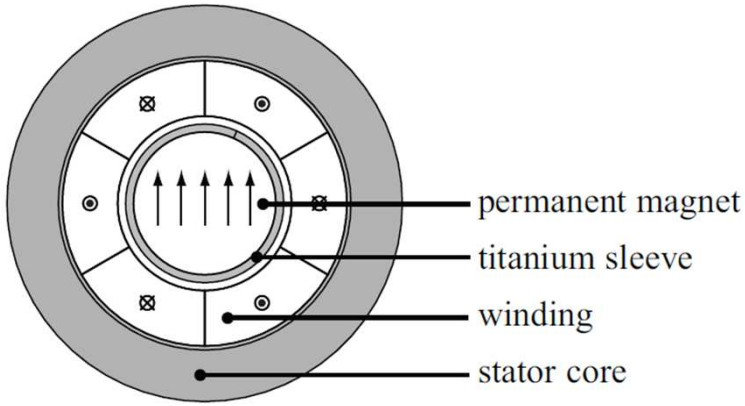
Working Principles

- Switched reluctance motors have high reliability
  - Lack of conductor coils and magnets on the rotor
  - Large core loss in the solid rotor at high speeds
- Brushless DC motors have high power density
  - Large harmonics of the back EMF cause large iron loss at high speeds
- Permanent magnet synchronous motor:
  - High efficiency due to no excitation power loss in the rotor
  - Low eddy current loss in the stator and rotor
  - High power densities due to strong magnets
  - Availability of rare-earth magnets

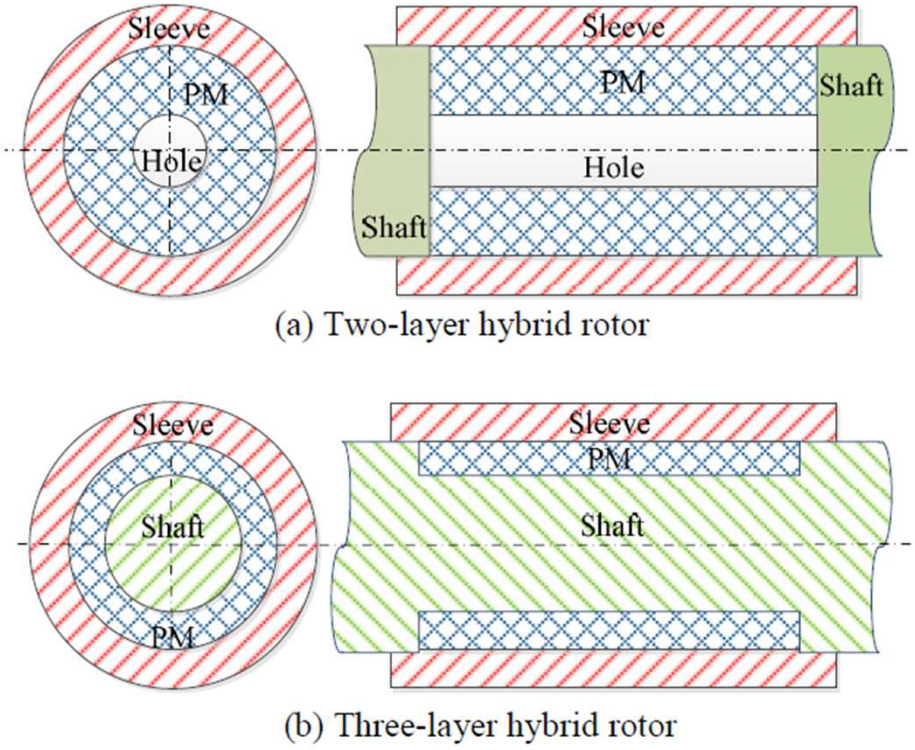
Working Principles



Flux lines of 2 kW, 200 krpm PMSM

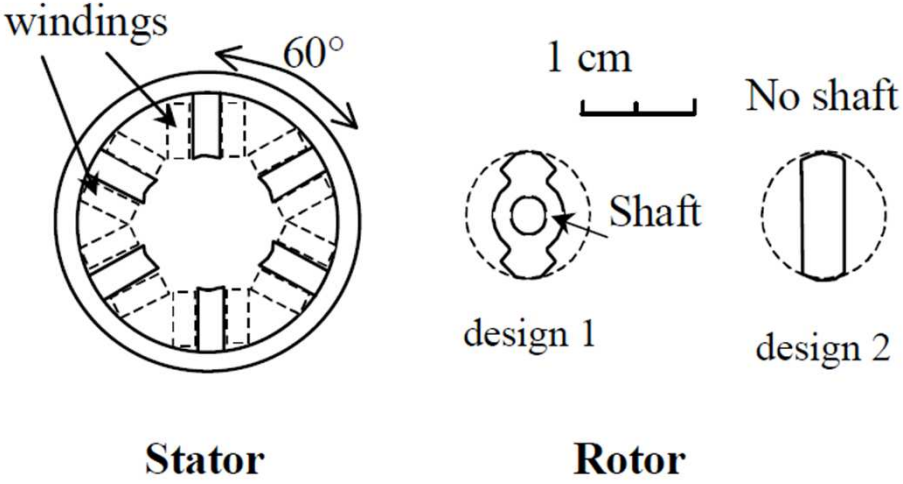


Slotless, three-phase, 1 kW,
500 krpm PM machine topology

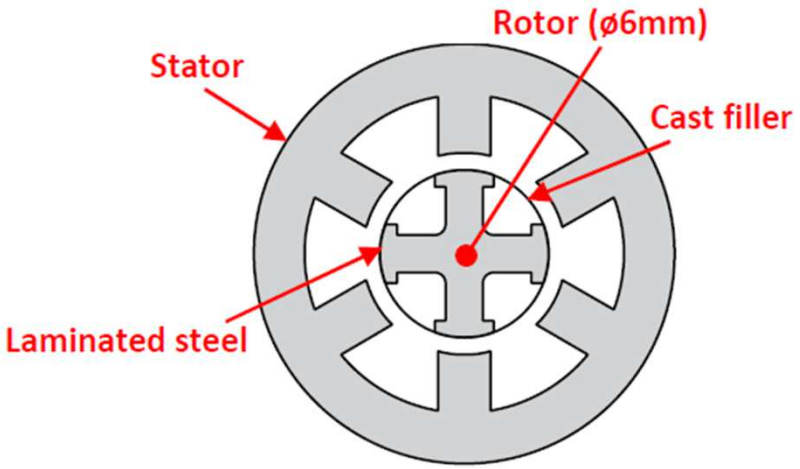


Two kinds of PM rotor structures

Working Principles



Stator and rotor section view of 1 kW, 200 krpm SRM



Section view of 750 krpm SRM

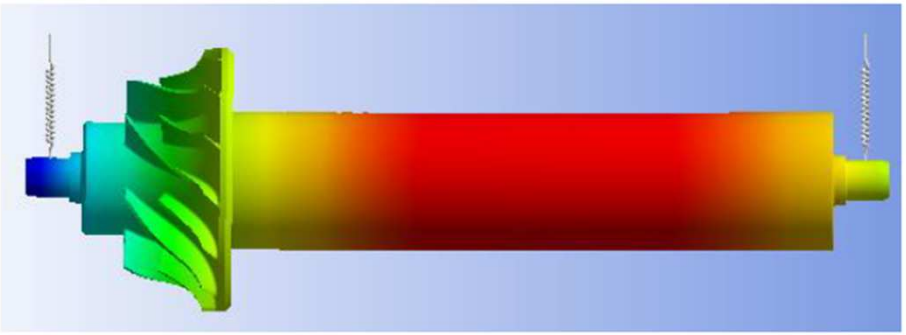
Advantages

- High efficiency, power density
- Small size, low weight
- Simple mechanics, easy maintenance
- Good reliability
- Decreased installation space
- No unnecessary gearboxes
- Applicability to various fields

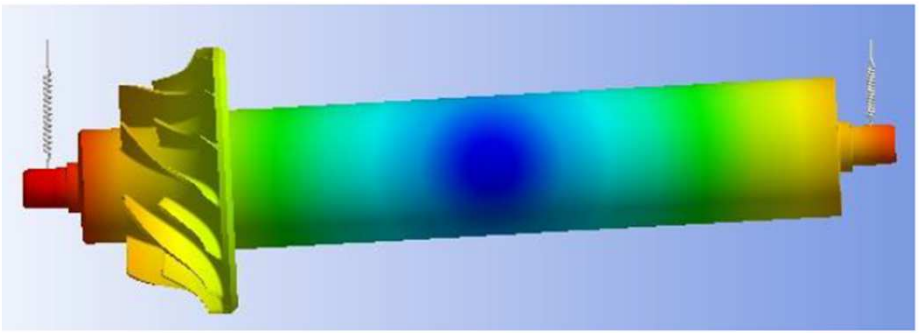
Challenges

- RPM*$\sqrt{kW}$ as a figure of difficulty in the mechanical design of machines [Keith, 2014]
- A low speed 3000 rpm / 660 MW turbine generator is mechanically more difficult to build than a high speed 100,000 rpm / 50 kW motor
- Mechanical factors such as stress and vibrations are likely to cause failure
- All electromagnetic, thermal, mechanical stress and structure dynamic aspects should be taken into account

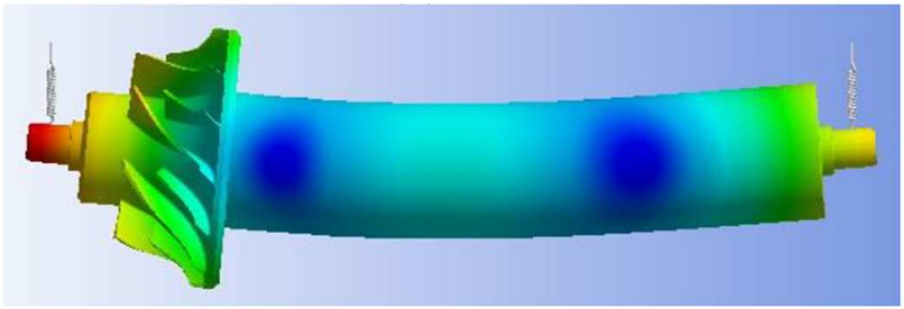
Challenges



(a)



(b)



(c)

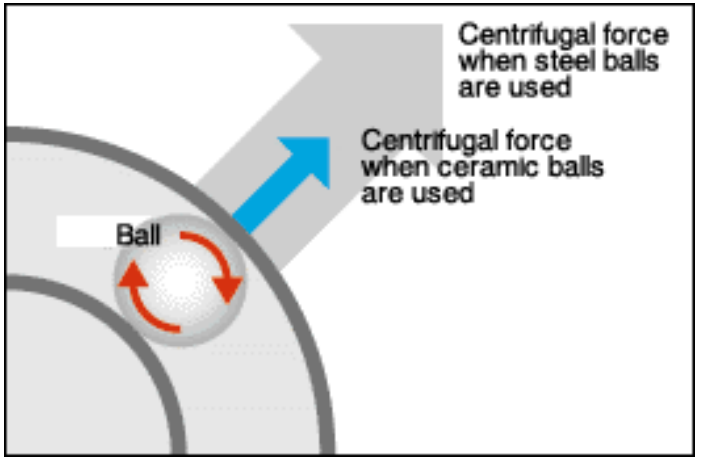
Critical speeds of the rotor of compressor

(a) First critical speed at 66,000 rpm
(b) Second critical speed at 156,000 rpm
(c) Third critical speed at 480,000 rpm

Blue indicates no displacement and red indicates maximum displacement.

Challenges

- Mechanical integration complications, critical speed, elasticity limit, careful design of bearings
- Small cooling surfaces due to very high power densities



- High centrifugal force, need for thin non-magnetic high-strength sleeves

Challenges

- Higher induced voltage, extra stress on the insulation
- Increased AC resistance due to high frequency and skin effect
- Limits of power electronic converters due to high switching frequency
- High bandwidth and high accuracy requirement in power measurement

Application Areas

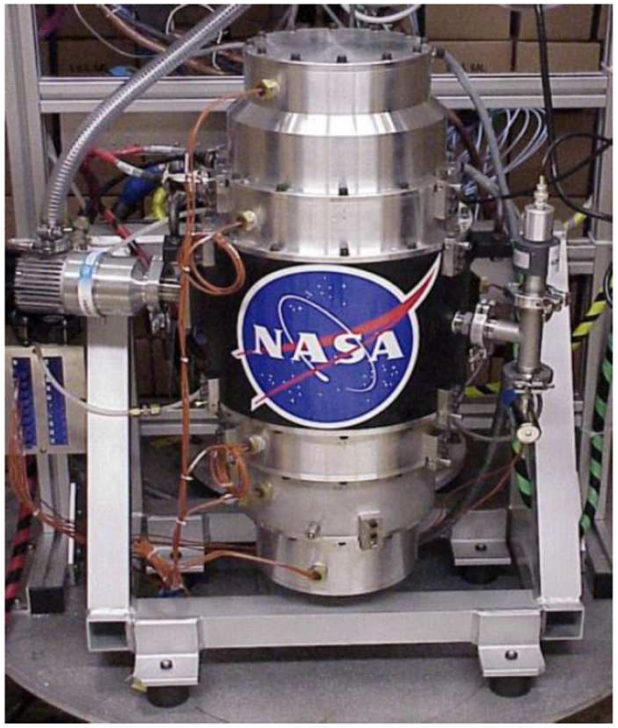
- Turbochargers, superchargers
- Spindles, machine tools
- Flywheel energy storage systems
- Compressors, pumps, centrifuges
- Distributed generation units (microturbines)

PCB spindle
(Up to 250,000 rpm, 200 W)

Stanford/M-DOT gas turbine
(800,000 rpm, 200 W)

Electric drive dental
hand piece

Application Areas



NASA G2 flywheel for attitude control and energy storage (night-day). (40,000 rpm, 3 kW motor/generator)

eBooster from BorgWarner – An electrically power air compressor providing pressurized air for the support of the turbocharger at low engine speeds (86,000 rpm, 720 W)

Conclusion

- Increased power density, compact design
- Higher performance and efficiency
- Prevelance of PM machines for ultra-speeds
- Electromagnetic, thermal, mechanical considerations due to material limits
- Various application areas including several machine tools and distributed generation units

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Thank you for
your attention