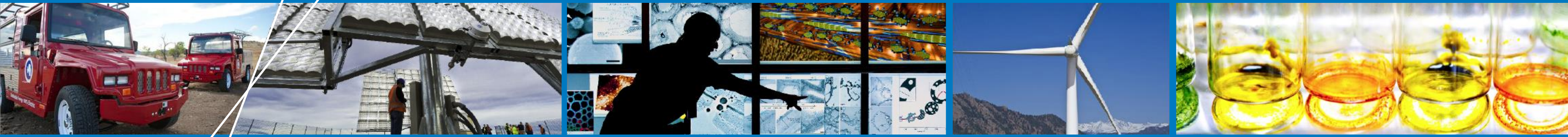
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Wind Turbine Generator for Distributed Wind Systems



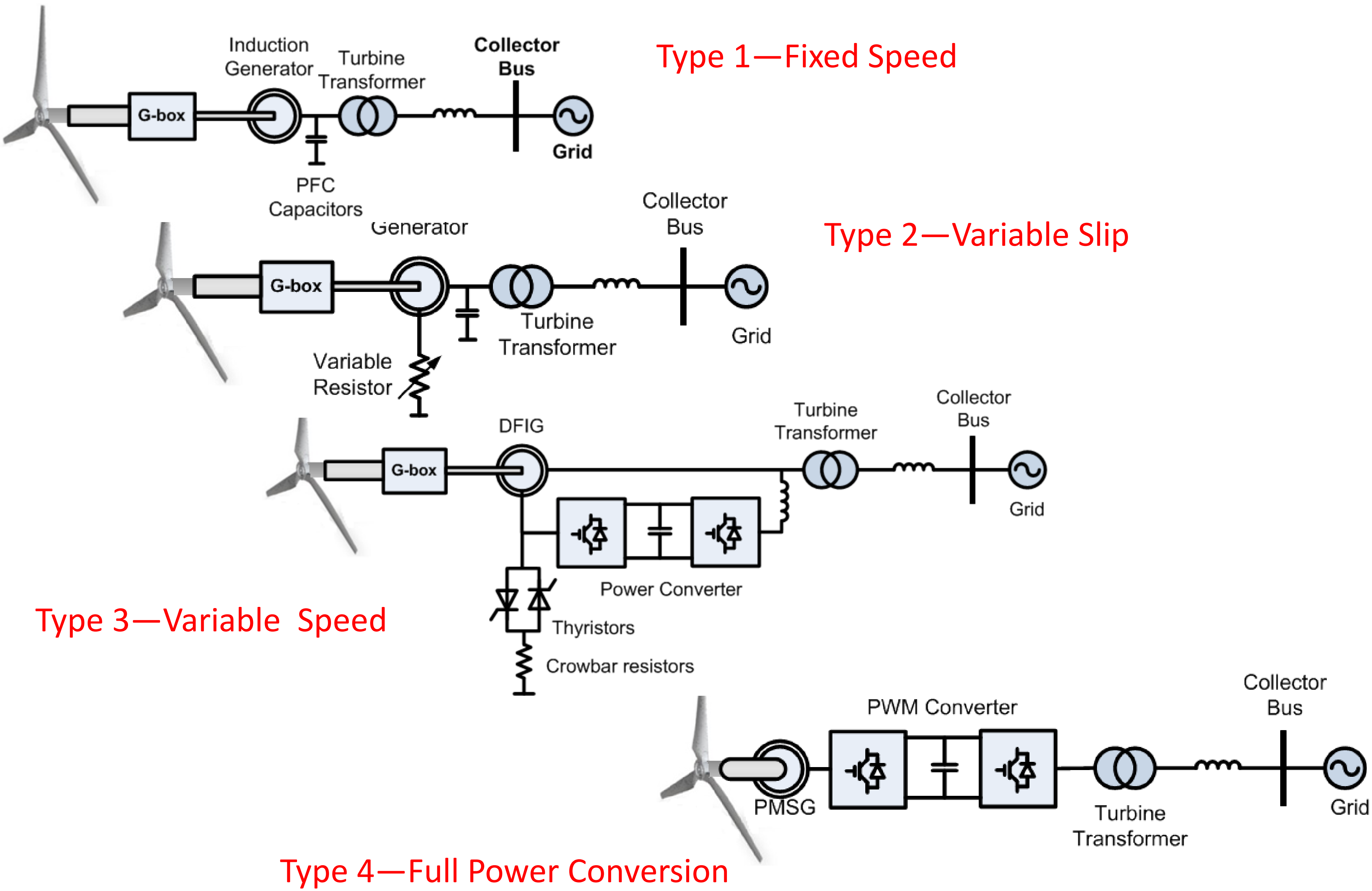
Distributed Wind Energy Association—Electrical Systems Subgroup Meeting

Eduard Muljadi

March 25–26, 2015

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Types of WTGs



Distributed Wind Turbine Progress

Then (1980s)

Technical

- Single-speed or dual-speed induction generator (fixed speed—Type 1)
- PM alternator with SCR base (harmonics, slow operation, line commutated)
- Aerodynamic control was primitive, mostly mechanical (furling/tilting—horizontal or vertical), pitch control—relatively new, mostly stall control

Cost

- PE had low power rating, slow switching, and was very expensive
- PM was ferrite (B = 0.3 Tesla), large and heavy machines
- Primitive control systems may lead to large mechanical-based system
- LCOE was heavily taxed by the CAPEX and OPEX

Now (2015)

Technical

- Variable-speed operation (DFIG—Type 3 or PMSG—Type 4)
- IGBT Si-based (800 V–1 kV), currently SiC-based (10—15 kV)
- Aerodynamic control (yaw, electro-mechanical servo-based), pitch control
- Modern control allows optimization in design, control, and energy capture

Cost

- PE is relatively cheap—e.g., Siemens chose exclusively Type 4 WTGs
- Rare earth PM (B = 1.4 Tesla), small, light machines
- Modern control allows optimization of size and dimension of the WTG
- LCOE (CAPEX and OPEX) has dropped significantly

Scaling Factors

Wind Turbine Scaling

$$P = 0.5\rho(\pi R_{blade}{}^{2})C_{pmax}(V_{wind})^{3}$$

$$R_{blade} = \sqrt{\frac{P}{0.5\rho(\pi)C_{pmax}V_{wind}{}^{3}}}$$

$$n = \frac{TSR^{*}\,V_{wind}}{2\pi\,R_{blade}}$$

$$n_{turb} = \frac{k_{turb}}{\sqrt{P}}$$

GE 1.5 MW = 22 rpm

10 kW gen ~ 270 rpm

Scaling Factors

Generator Scaling

$$n_{gen} = \frac{P}{(D^2\ L)\,(\,Eff\ \ B\,J\,pf\ )}$$

Volume k_{gen}

$$n_{gen} = \frac{P}{Vol\ k_{gen}}$$

higher rpm = higher power density

* For the same power (P), the volume is proportional to the rotational speed (n)

* Increasing k_{gen} will impact the volume as well

Scaling Factors

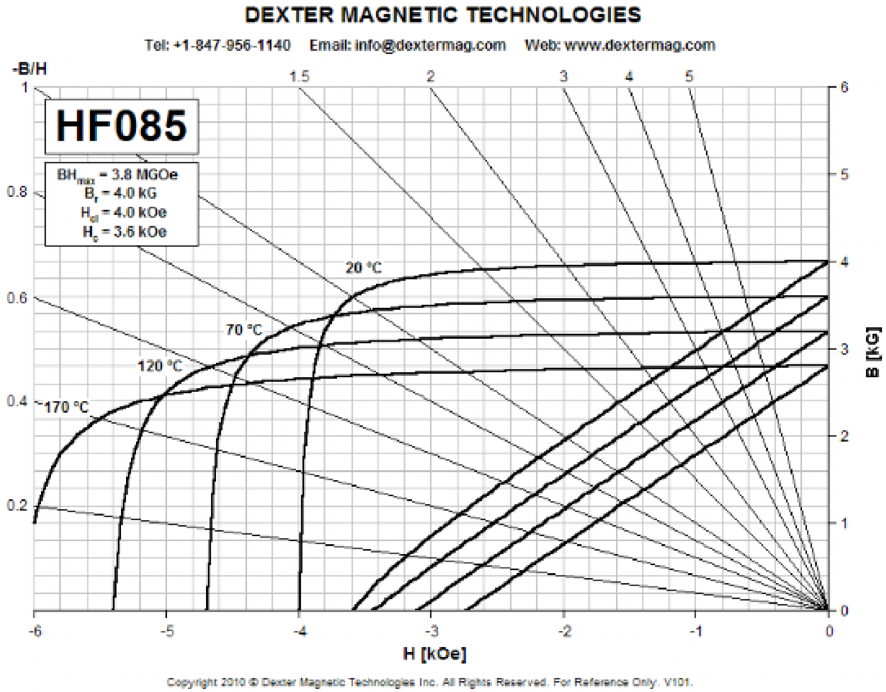
Generator Scaling

Increasing K_{gen}

- Eff = efficiency – mechanical and electrical (winding/copper losses and iron losses)
- B = magnetic flux density (Silicon Steel B ~ 1.8 Tesla; PM: Br ~ 0.4 T – 1.45 T)
- J = electrical current density (max for copper = A/mm^2)
- pf = power factor of the output of the generator (max if output at unity power factor)

Permanent Magnet

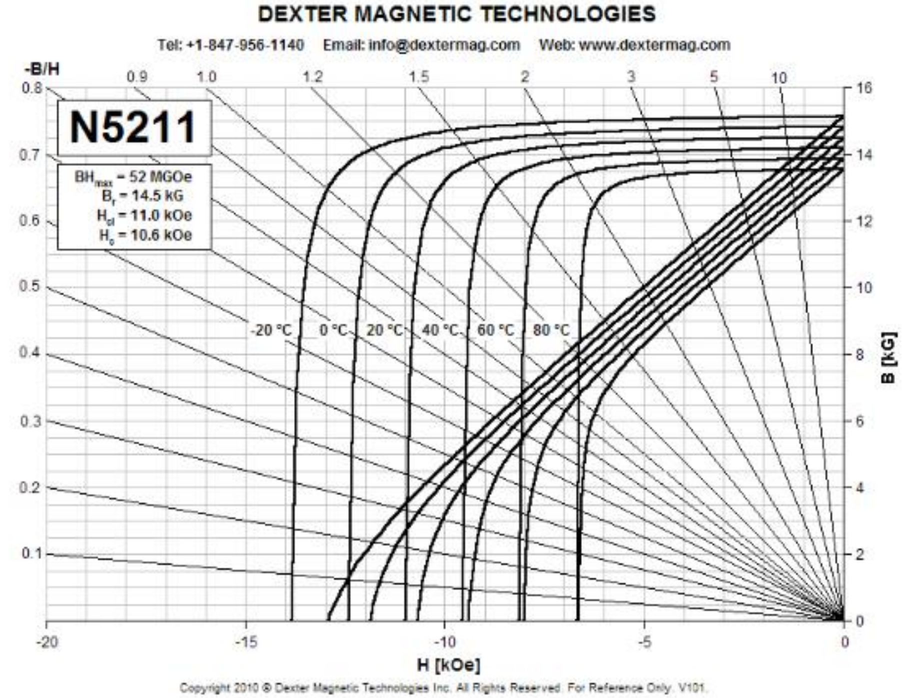
Ferrite



Grade	Maximum Energy Product BHmax	Residual Induction Br	Minimum Intrinsic Coercivity Hci	Coercivity Hc	Maximum Operating Temp Tmo	Curie Temp Tc	Coefficient Induction 20-150 °C α	Coefficient Coercivity 20-150 °C β
	MGOe	kG	kOe	kOe	°C	°C	% / °C	% / °C
HF085	3.8	4.0	4.0	3.6	250	450	-0.20	0.35

Neodymium Iron Boron

(NdFeB)



Grade	Maximum Energy Product BHmax	Residual Induction Br	Minimum Intrinsic Coercivity Hci	Coercivity Hc	Maximum Operating Temp Tmo	Curie Temp Tc	Coefficient Induction 20-150 °C α	Coefficient Coercivity 20-150 °C β
	MGOe	kG	kOe	kOe	°C	°C	% / °C	% / °C
N5211	52	14.5	11	10.6	50	310	-0.12	-.065

Stator Core

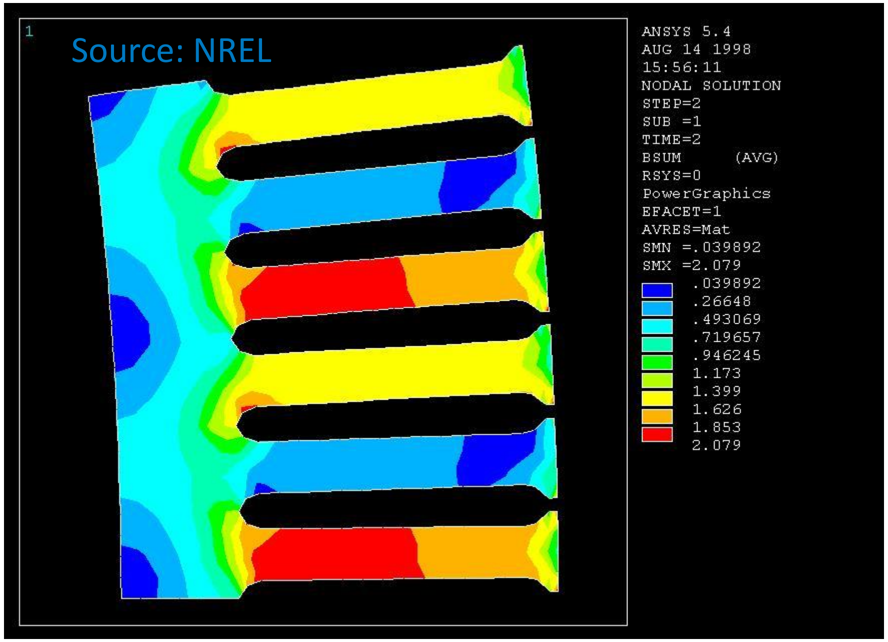
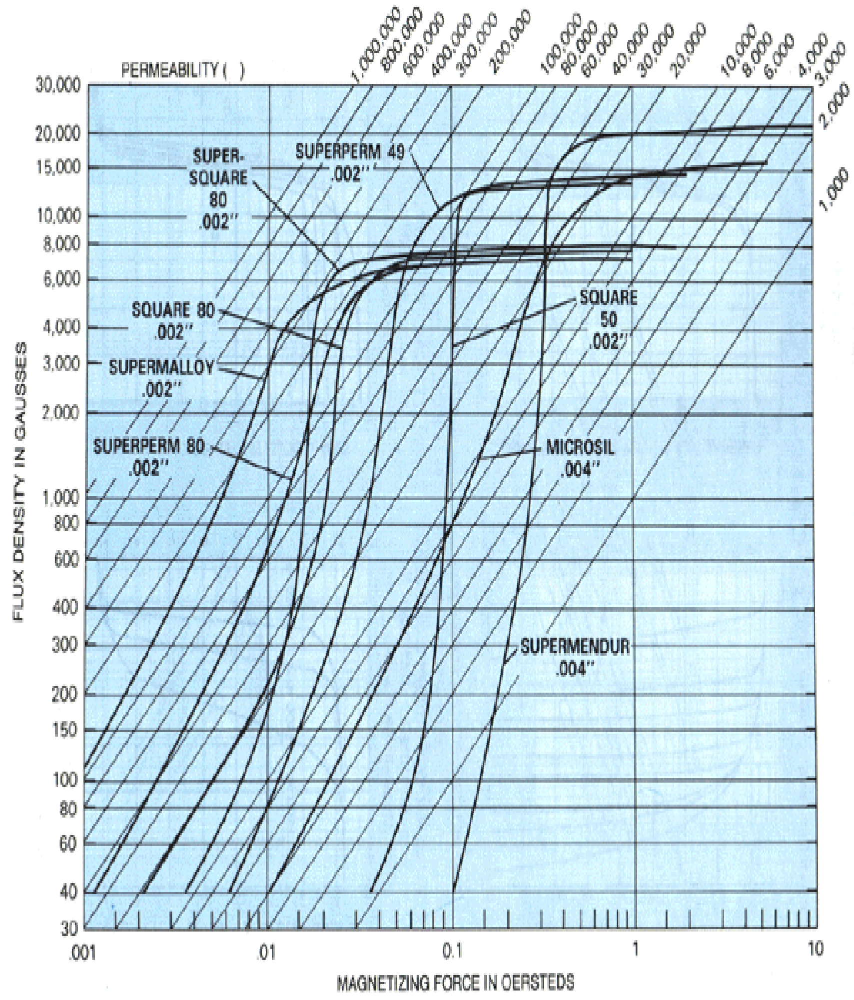


Image from http://www.tempel.com/products/

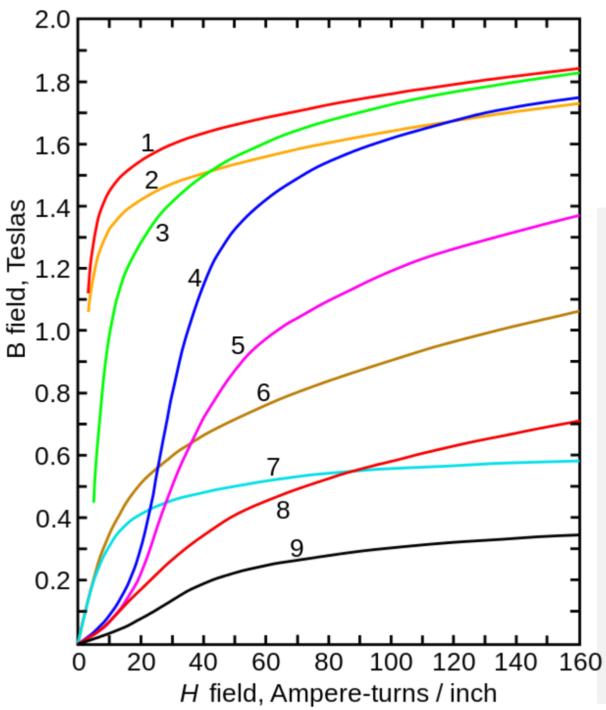
Image from http://www.magmet.com/tapewound/magnetic.php



Stator Laminations

Helical Winding

As an industry leader, we're proficient in winding lamination steel strips into an electro-magnetic core. By winding the steel into a laminated core, efficiency is increased, waste is minimized and the steel produces electrical conductivity, enabling the magnetic path to be completed. Thus, generating the maximum amount of power while using the least amount of raw material.



“Magnetization curves” by Charles Proteus Steinmetz. Tracing of graph from Steinmetz, C. (1917). *Theory and Calculation of Electric Circuits.* New York: McGraw-Hill; p. 84, fig. 42 on Google Books. Public Domain via Wikimedia Commons: http://commons.wikimedia.org/wiki/File:Magnetization_curves.svg#/media/File:Magnetization_curves.svg

Notching

Tempel produces large diameter laminations for the industrial, hermetic, specialty and traction motor markets, as well as a variety of generator applications. Our advanced automated notching technology gives us the ability to stamp rotor and stator laminations while providing process and cost advantages over traditional manual operations.

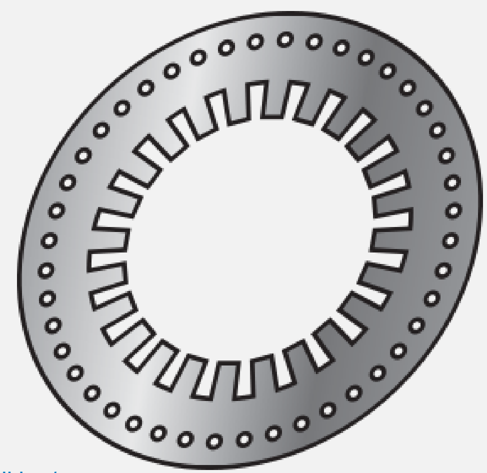


Image from http://www.tempel.com/capabilities/

Mathematical Modeling

Source Sink

$$J\ddot{\delta}(t) = \tau_{aero}(t) - \tau_{gen}(t)$$

Source

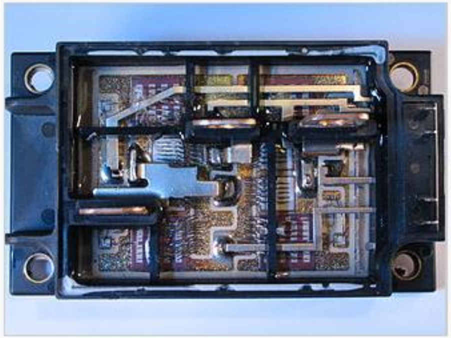
$$\tau_{aero}(t) = \tau_{mech-ave}(t) + \tau_{turbulence}(t) + \tau_{pitch\&yaw}(t) + \tau_{mech-brake}(t)$$

Sink

$$\tau_{gen}(t) = \tau_{gen-ave}(t) + \tau_{damp}(t) + \tau_{aux}(t)$$

Electrical Stresses

IGBT-Module (IGBTs and freewheeling diodes) with a rated current of 1,200 A and a maximum voltage of 3,300 V

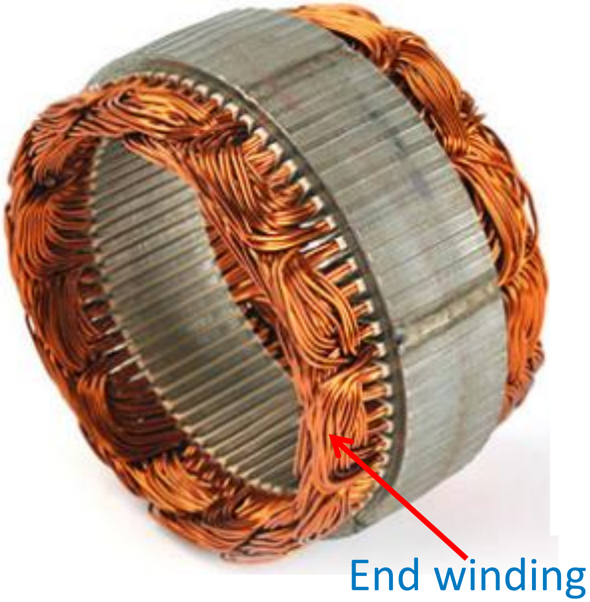


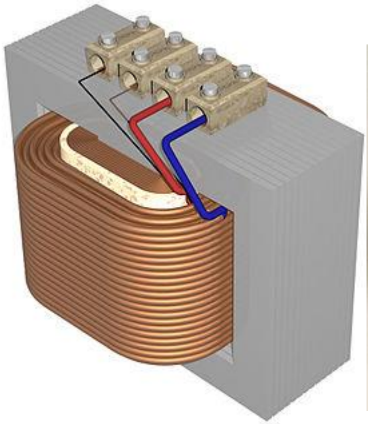
Opened IGBT module with four IGBTs (half of H-bridge) rated for 400 A 600 V

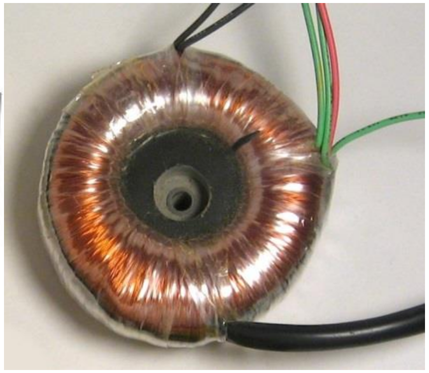
Small IGBT module, rated up to 30 A, up to 900 V

Power Electronics

Images from Wikipedia







Winding Insulations

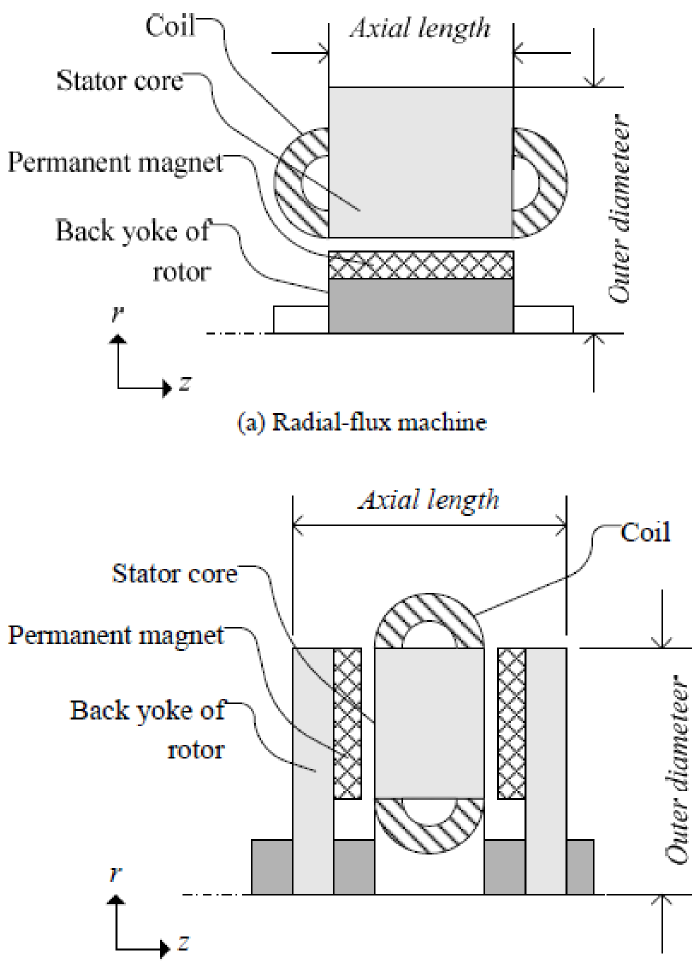
Image from *http://www.tempel.com/products/motor-generator/*

Images from Wikipedia

Generators

- **Types of Generators**
  - Axial flux, radial flux PM generator
  - Toroidal winding
  - Reluctance generator
  - Flux switching generator
  - Brushless synchronous generator
  - Capacitive generator

Radial Flux Generator



(a) Radial-flux machine

(b) Axial-flux machine (Double rotor)

Fig. 1. Structure of the machines

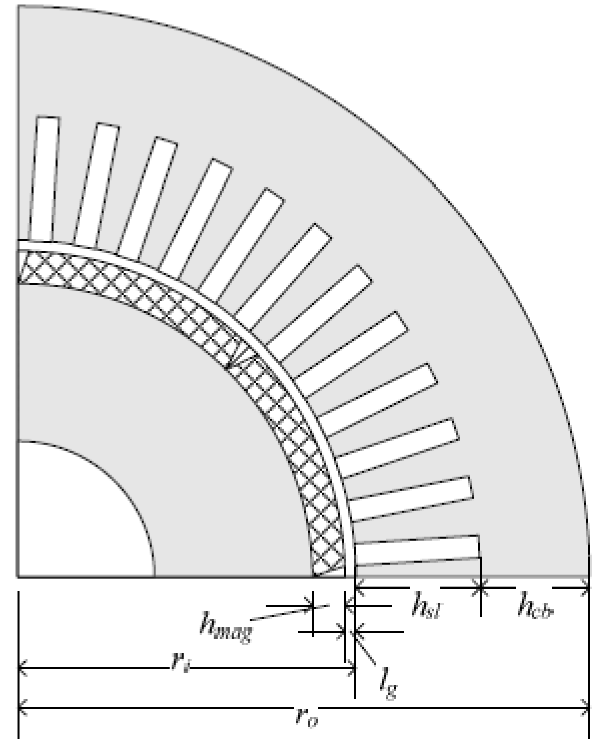
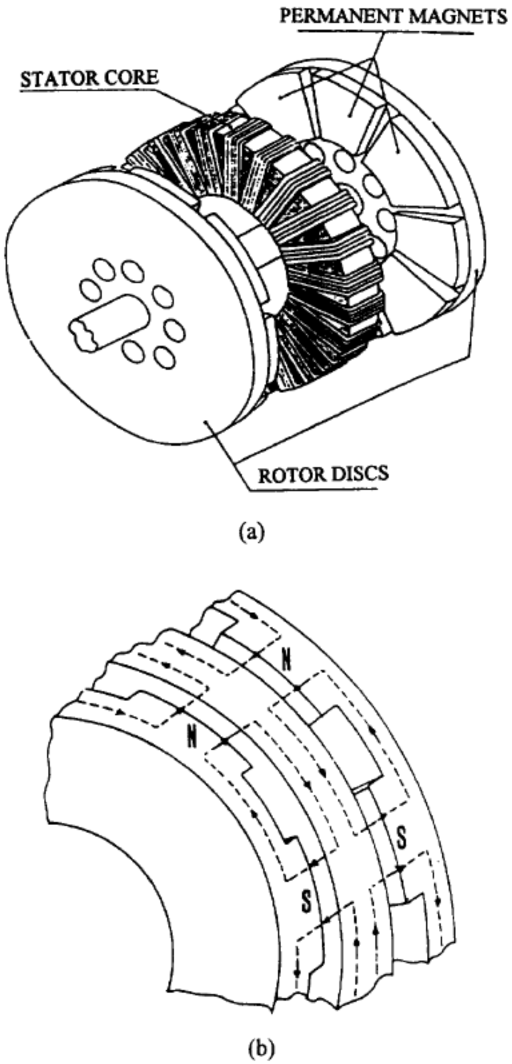


Fig. 2. Dimensions of radial-flux machine

Nakahara, A., et al. (2014). "Comparative Electrical Design of Radial- and Axial-Flux Permanent Magnet Synchronous Machines under Space Limitation." Presented at the ICEM International Conference on Electrical Machines; Sept. 2–5, 2014, Berlin, Germany.

Axial Flux PM Generator



Basic structure of (a) slotless axial-flux PM machines and (b) related flux path

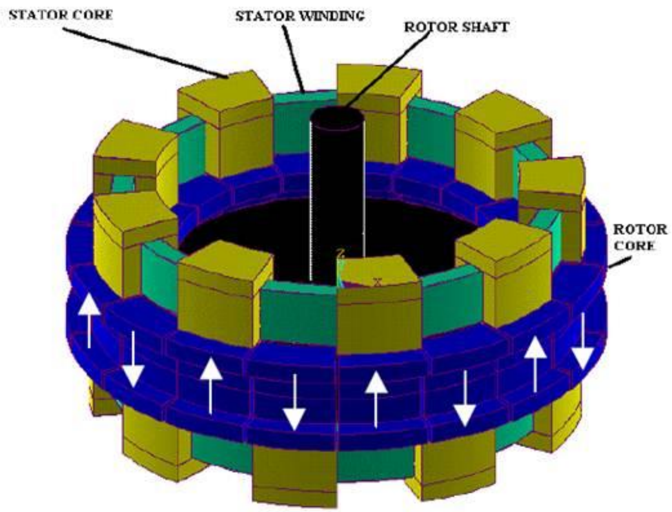
Typical characteristics

- Permanent magnet on both sides of the rotating rotors
- Slotless configuration
- Excitation provided by PM
- High efficiency
- Requires power converter for variable-speed operation

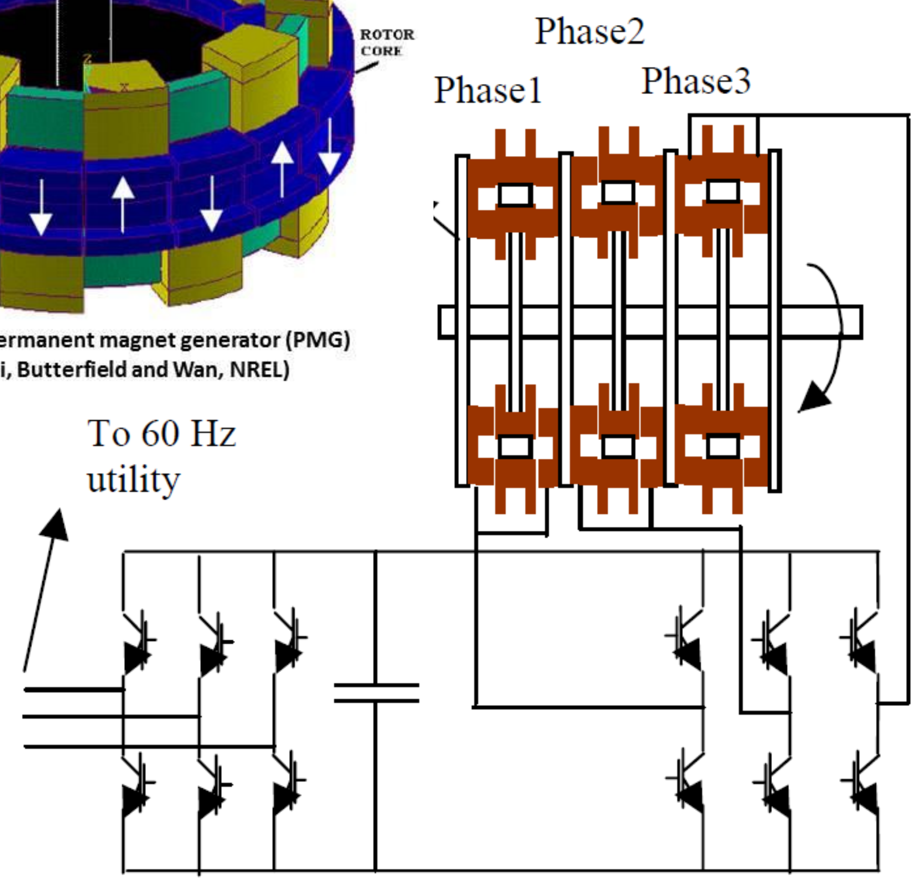
Toroidal Winding AFPM Modular Generator

Typical characteristics

- Stator coils on both sides of the rotating rotors
- Toroidal winding
- Flux-focusing PM
- Modular concept
- High efficiency
- Power converter for variable-speed operation



Schematic of a permanent magnet generator (PMG)
(from Muljadi, Butterfield and Wan, NREL)



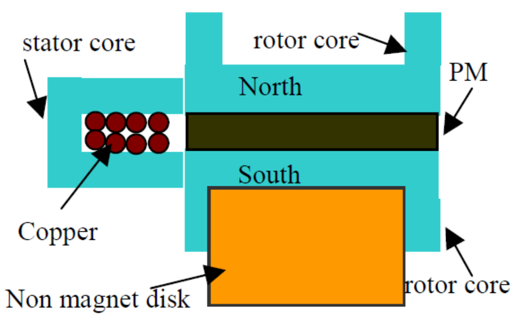
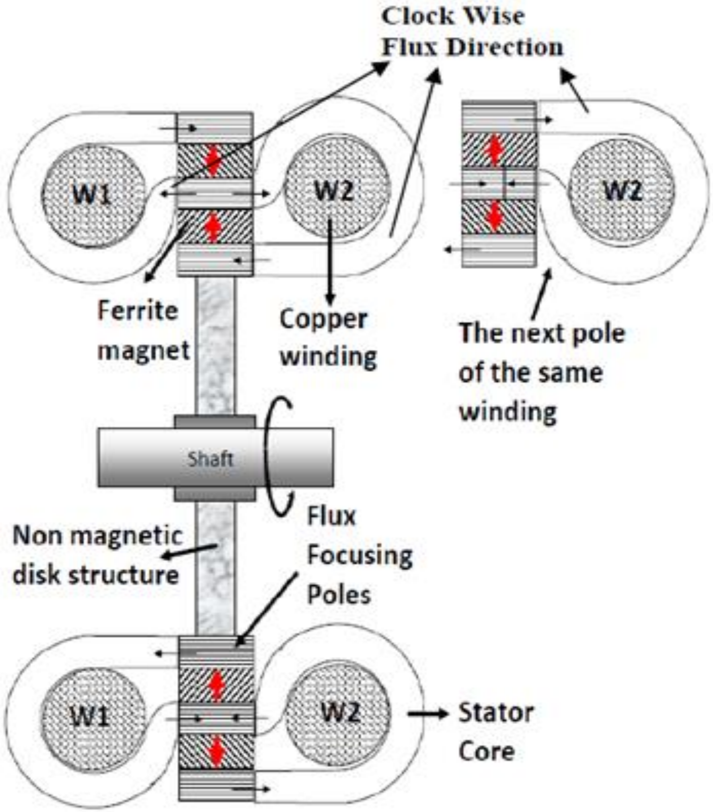
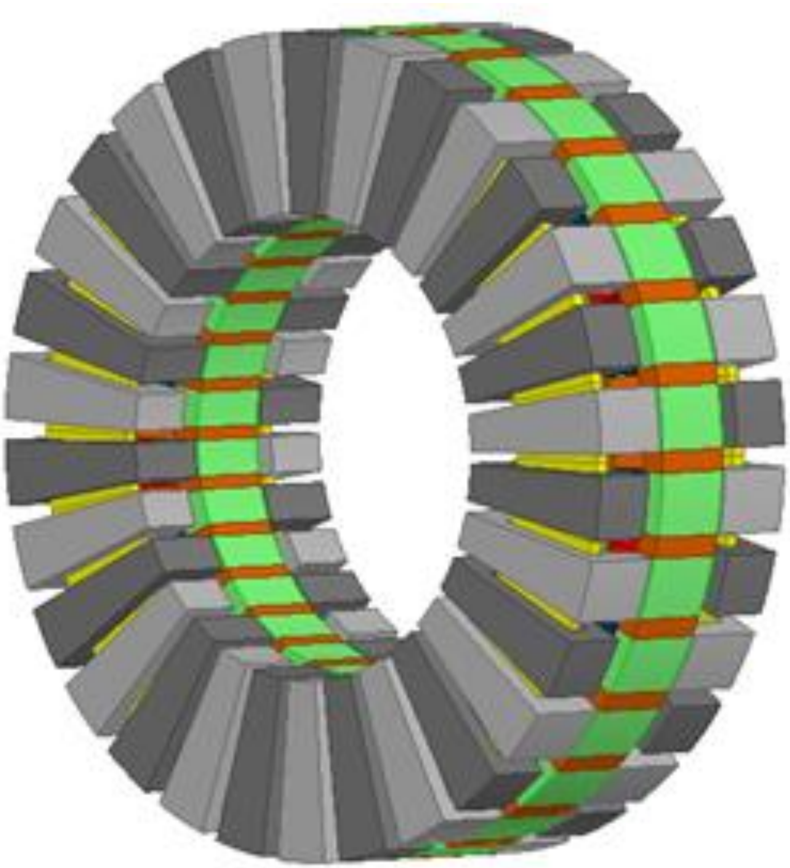


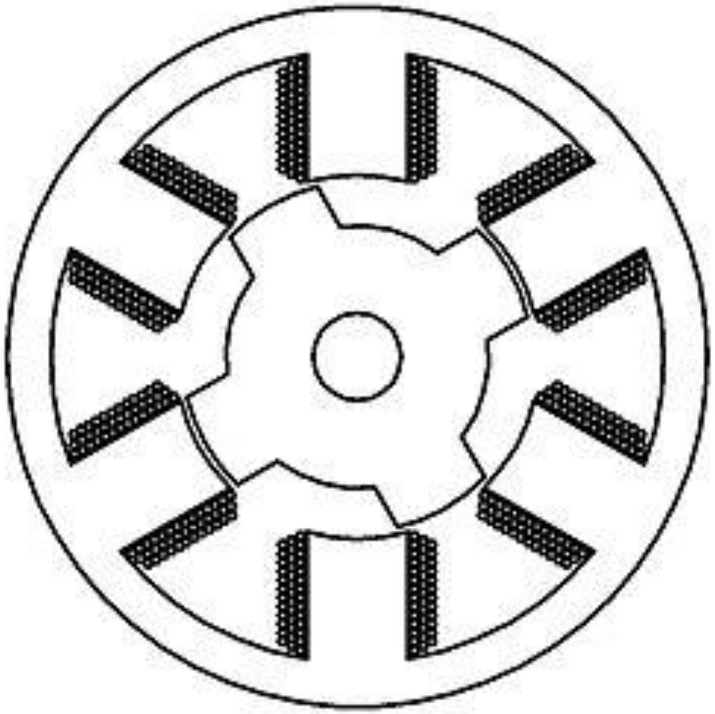
Figure 1. One pole of the stator and rotor core

Toroidal Winding AFPM Modular Generator





Switched Reluctance Generator



Cross-section of switched reluctance machine with six stator and four rotor poles. Notice the concentrated windings on the stator poles. *Image from Wikipedia*

Typical characteristics

- No permanent magnet
- Excitation provided by stator
- Requires power converter for variable-speed operation
- Larger than PM generator
- Noise
- Direct-drive option
- Cost advantage

Image from http://www.digikey.com/en-US/articles/techzone/2012/sep/ev-drive-electronics-evolve-to-support-rare-earth-free-motor-technologies

Flux Switching Machine

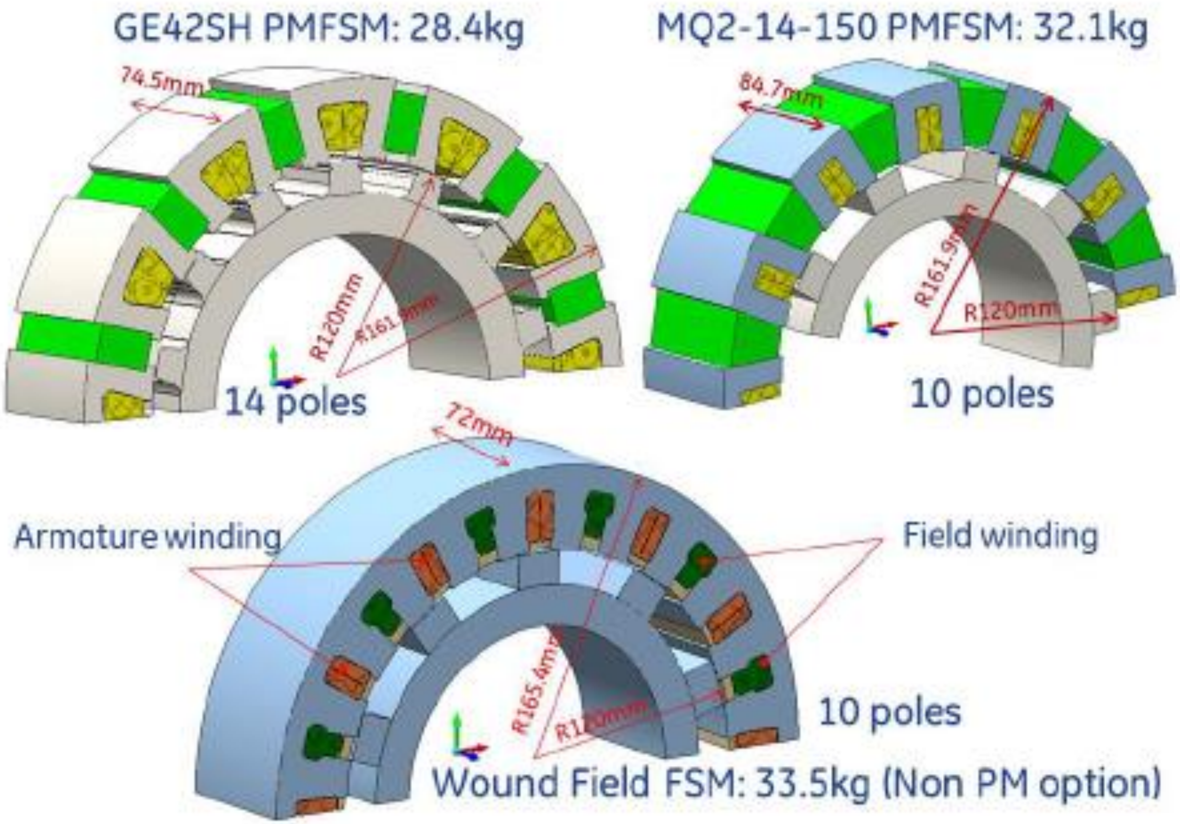


Figure 4. Flux Switching Machine Options Under Consideration.

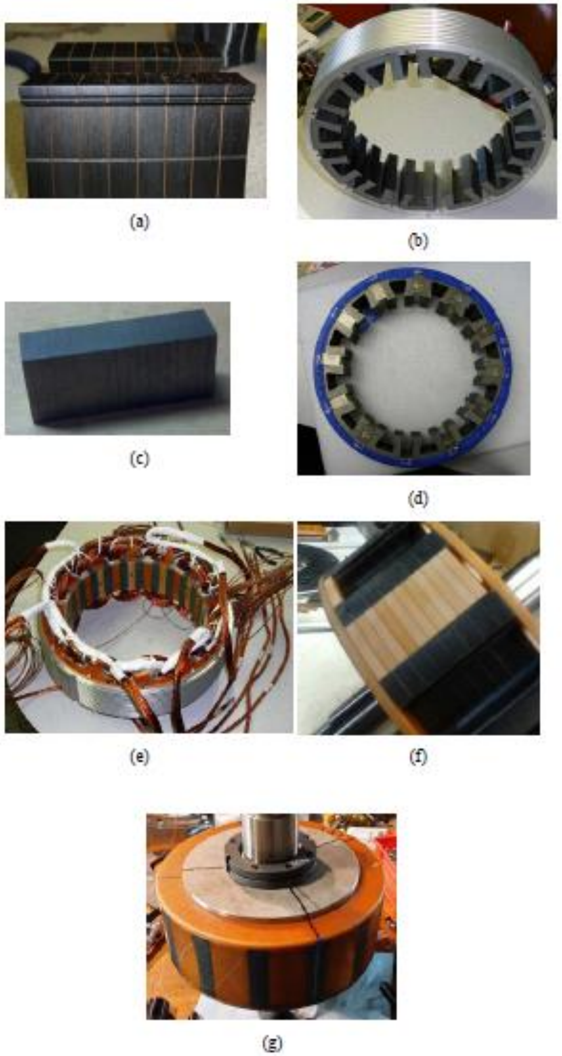


Figure 18. Prototype Photographs: (a) Laminated Stator C-core including Copper Laminations; (b) Laminated Magnet Block; (c) C-cores Shrink-Fitted onto Inner Cooling Jacket; (d) Sator with Magnets Inserted; (e) Wound Stator; (f) Rotor including Copper Laminations and composite non-magnetic wedges and end plates; (g) Completed Rotor.

Raminosoa, T., et al. (2014). "Reduced Rare-Earth Flux Switching Machines for Traction Applications." *IEEE Energy Conversion Congress and Exposition Proceedings*; Sept. 14–18, Pittsburgh, Pennsylvania.

Brushless Synchronous Generator

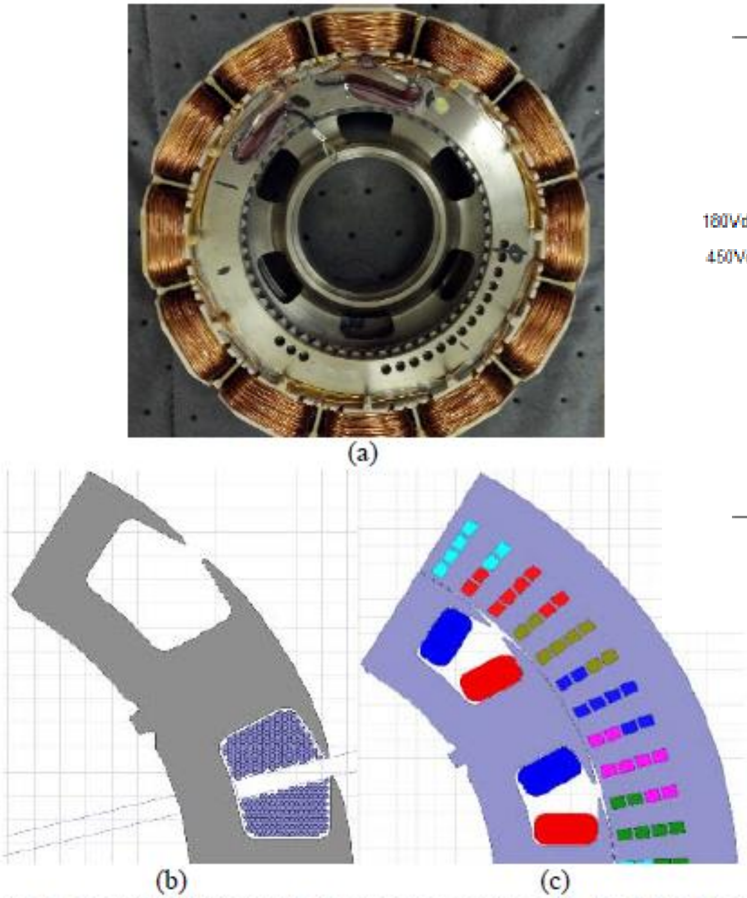


Figure 1. The SESM rotor with the winding in place (a), the SESM rotor with the cross sectional view of the slot showing the winding placement (b), the complete motor geometry (c).

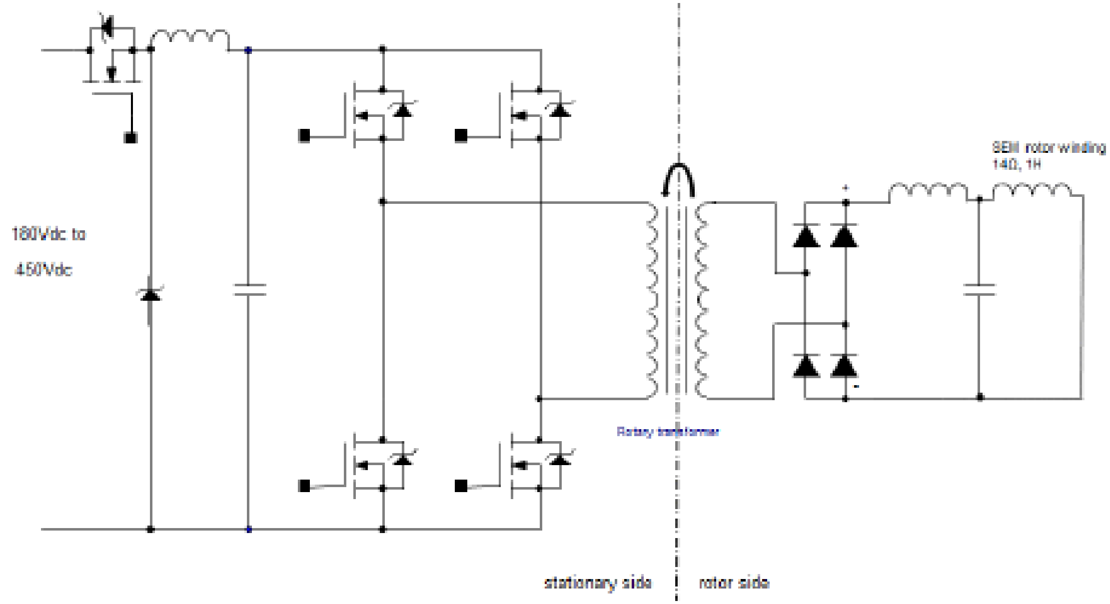


Figure 3. Field Power Converter topology

Stancu, C.; et al. (2014). "Separately Excited Synchronous Motor with Rotary Transformer for Hybrid Vehicle Application." *IEEE Energy Conversion Congress and Exposition Proceedings*; Sept. 14–18, Pittsburgh, Pennsylvania.

Capacitive Generator

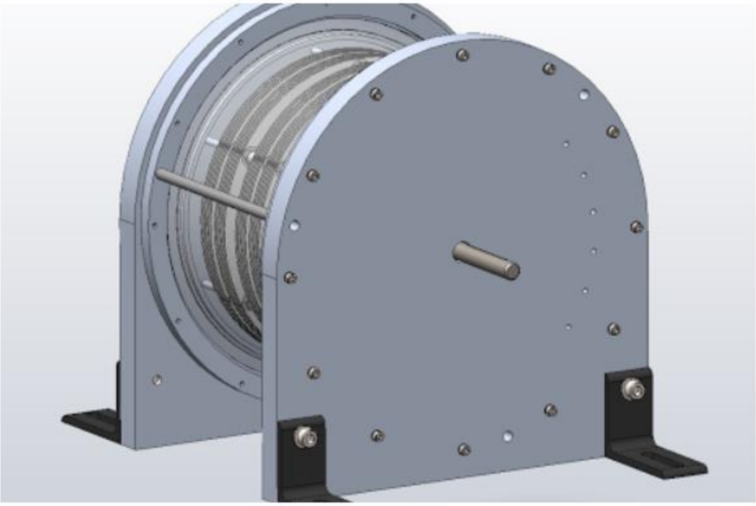


Image from http://www.c-motive.com/our-technology-products/

C-Machine Capacitive Machine

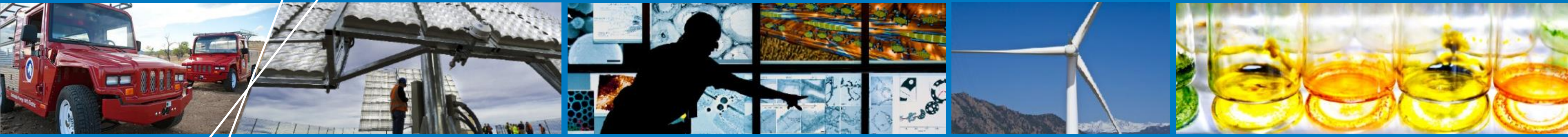
- Electrostatic motor designed as a full replacement for existing motors and generators
- Produces high torque at low speed
- All aluminum and recyclable
- Lightweight
- Does not require a gearbox
- Achieves smooth rotation and minimal noise
- Designed to operate at 95% efficiency, cutting energy loss by a factor of three compared to conventional motors

Status: Prototype nearing completion.
Will begin beta testing in 2014.

Summary

- **Progress has been made in technical areas**
  - Permanent magnet: B = 1.5 Tesla
  - Power electronics: SiC devices up to 15 kV, high temperature, high switching frequency, high efficiency
  - Stator core lamination: Supermendur up to 2 Tesla
  - Many different topologies have been introduced in electric machine design, power converter design, and control algorithms
- **Main challenges**
  - Low volume, low profit margin = lack of interest from manufacturers
  - Interconnection regulations, tax incentives

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.



Thank you for your interest!

Questions?