NSF Funded Research on Electrical Machines

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Grainger CEME/IEEE Workshop on Technology Roadmap for Large Electrical Machines
University of Illinois, Urbana-Champaign
April 5-6, 2016

Outline

- General Comments on NSF Funding
- Energy, Power, Control and Networks (EPCN) Program
- NSF/EPCN-Funded Electrical Machines Projects

Unique Features of NSF

- Supports **fundamental research and education** across all fields of science and engineering
- Discipline-based structure with cross-disciplinary mechanisms
- Emphasis on integrating research and education
- Close interaction with universities
- Rotator System: About 50% Program Directors are on loan from universities, labs, or industries

NSF Funding is Largely Community-Driven

- Many programs and solicitations.
- The unsolicited proposal program is basic at NSF, and PI's can propose their ideas to programs.
- Even large multi-investigator programs like ERC's, STC's, EFRI proposals, IUCRC's, etc. involve a large degree of bottom-up activity.
- The community can propose initiatives to Program Directors on topics that they believe deserve concentrated effort by several (or many) research groups. These can lead to Dear Colleague Letters (DCL's) soliciting two year EAGER proposals on a topic or larger initiatives.

NSF ENG Organization

Office of the Assistant Director

Assistant Director

Deputy Assistant Director

- Emerging Frontiers in Research and Innovation (EFRI)
- Program Director Evaluation and Assessment
- Senior Advisor for Nanotechnology
- Program Director for I-Corps

- Engineering Education and Centers (EEC)
- Chemical, Bioengineering, Environmental, and Transport Systems (CBET)
- Civil, Mechanical, and Manufacturing Innovation (CMMI)
- Electrical, Communications, and Cyber Systems (ECCS)
- Industrial Innovation and Partnerships (IIP)

Electrical, Communications and Cyber Systems (ECCS) Division

- Electronics, Photonics, and Magnetic Devices
- Communications, Circuits, and Sensing Systems
- Energy, Power, Control and Networks

Energy, Power, Control and Networks (EPCN) – A Core Program

- Design and analysis of complex systems including sensing, imaging, control and computational technologies
- Emphasis on electric power systems, especially with renewable energy integration
- Power electronics, electrical machines and drives
- Energy harvesting devices and systems
- Regulatory and economic structures for power and energy

NSF/EPCN is a Resource for the Community

- We are a resource and would like to work with the community to help move the fields that we support forward.
- Please provide your creative ideas for ensuring excellent research going forward in your field.
- This includes both research and education.

Electric Power Systems

- Critical infrastructure for society
- System is evolving rapidly with increase of DG and renewable sources, and need to reduce carbon footprint
- Large scale spatially distributed nonlinear dynamic systems with multiple time scales requiring advanced hierarchical/distributed control, sensors, algorithms, economic markets
- Evolving power sources requires research on new electrical machine concepts and power electronics

A Useful Tool: NSF Award Search

- Go to Google and search for "NSF award search." Then you can find grants satisfying keywords like "electrical machines."

- Or you can go to www.nsf.gov
  - Search awards
    - Advanced search
      - Program officer
- Many options available
  - Program Information
  - Keyword search, such as "Wind Energy" "Power Systems" "Power Electronics" "Energy Harvesting"…

Sample Funded Electrical Machines Projects

- **Ned Mohan, Lead on CUSP program, Minnesota:**
  - **Modular Multilevel Converter (MMC)-based Power Electronic Transformer, Minnesota**
  - **Web-Enabled, Instructor-Taught Online Courses (ONR grant; also similar support from NSF)**
  - **Electrical Energy Systems Education with Emphasis on Sustainable Power, NSF**
- **Ali Davoudi, Real-time Ab-Initio Modeling of Electric Machines, UT Arlington**
- **Bulent Sarlioglu, Wisconsin**
  - **CAREER: Novel Integration of Fluid Dynamic Design into Electric Machines**
  - **GOALI: Novel Flux Switching Permanent Magnet Machine for Emerging and Renewable Energy Systems**

Funded Electrical Machines Projects, Cont'd.

- Dan Ludois, Electrostatic Machines (CAREER), Wisconsin
- Iqbal Husain, Direct-Drive Modular Transverse Flux Electric Machine without Using Rare-Earth Permanent Magnet Material, NC State
- Jonathan Bird, Magnetically Geared Renewable Energy Generators, Portland State (formerly UNC Charlotte)
- Dionysios Aliprantis, Sculpting Electric Machines for Unidirectional Motion , Purdue
- Elias Strangas, GOALI: Failure Diagnosis and Mitigation in Permanent Magnet AC Machines, Michigan State

NSF/EPCN-Funded Electrical Machines Projects: Detailed Descriptions of Efforts

The subsequent slides are based on content kindly provided by the Principal Investigators of these and related projects.

Electrical Energy Systems Education with Emphasis on Sustainable Power *(ECCS-0901635/1028326, Mohan, University of Minnesota – Twin Cities)*

(Supported by NSF, NASA, ONR, DOE and EPRI)

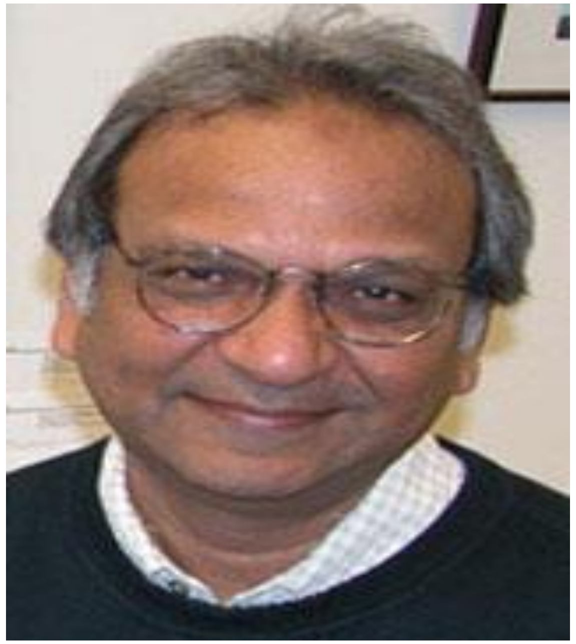
145 Universities

Consortium of Universities for Sustainable Power (CUSP) ™

Vision: Revitalizing Electric Energy Systems Education worldwide through proactive dissemination and the Internet using CUSP™

Outcomes:

- Power & Energy Curriculum
- Undergraduate & Graduate Courses
- Workshops
- Laboratories
- Student Enrollment
- Published Textbooks

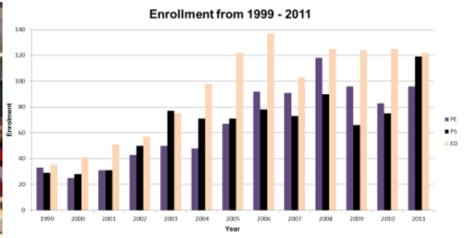


Professor Ned Mohan

University of Minnesota

S&T OBJECTIVES

- Develop a Graduate and undergraduate curriculum in Electric Energy Systems and disseminate it widely to all U.S. universities
  - ➢ A better-trained supply of U.S. graduates in STEM to tackle various research challenges in the Navy



APPROACH

- Develop a complete curriculum (undergraduate and graduate) and disseminate widely; teach these courses online towards a master’s degree
- A total of 19 graduate-level courses will be uploaded to the dissemination portal (www.cusp.umn.edu):
- Organize an yearly workshop and invite ECE faculty, Dept Heads and Engineering Deans to participate.

RESULTS / IMPACT

- Over 100 U.S. universities are using UMN-developed curriculum
- A Consortium of Universities for Sustainable Power (CUSP™) has been established
  - ➢ www.cusp.umn.edu is the dissemination portal
  - ➢ This consortium is joined by 216 U.S. universities
- Yearly workshop is organized and it is attended by a large number of U.S. ECE faculty, Department Heads and Engineering Deans.
  - ➢ Our most recent workshop in Washington, DC during April 2015 was attended by nearly 150 faculty.
  - ➢ The next workshop is organized to be in Minneapolis, MN during July 6-8, 2016.

S&T OBJECTIVES

- Develop a Graduate and undergraduate curriculum in Electric Energy Systems and disseminate it widely to all U.S. universities
- Teach these courses online to Practicing Engineers towards a master's degree
    - **A better-trained supply of U.S. graduates in STEM to tackle various research challenges in the Navy**

Application Areas

Electricity Generation, Transmission and End-Use:

- Reliable , Robust, Smarter Grid
- Renewables/storage
- Increased Energy Efficiency – Climate Change

Transportation

- Trains
- Planes
- Hybrids/EVs

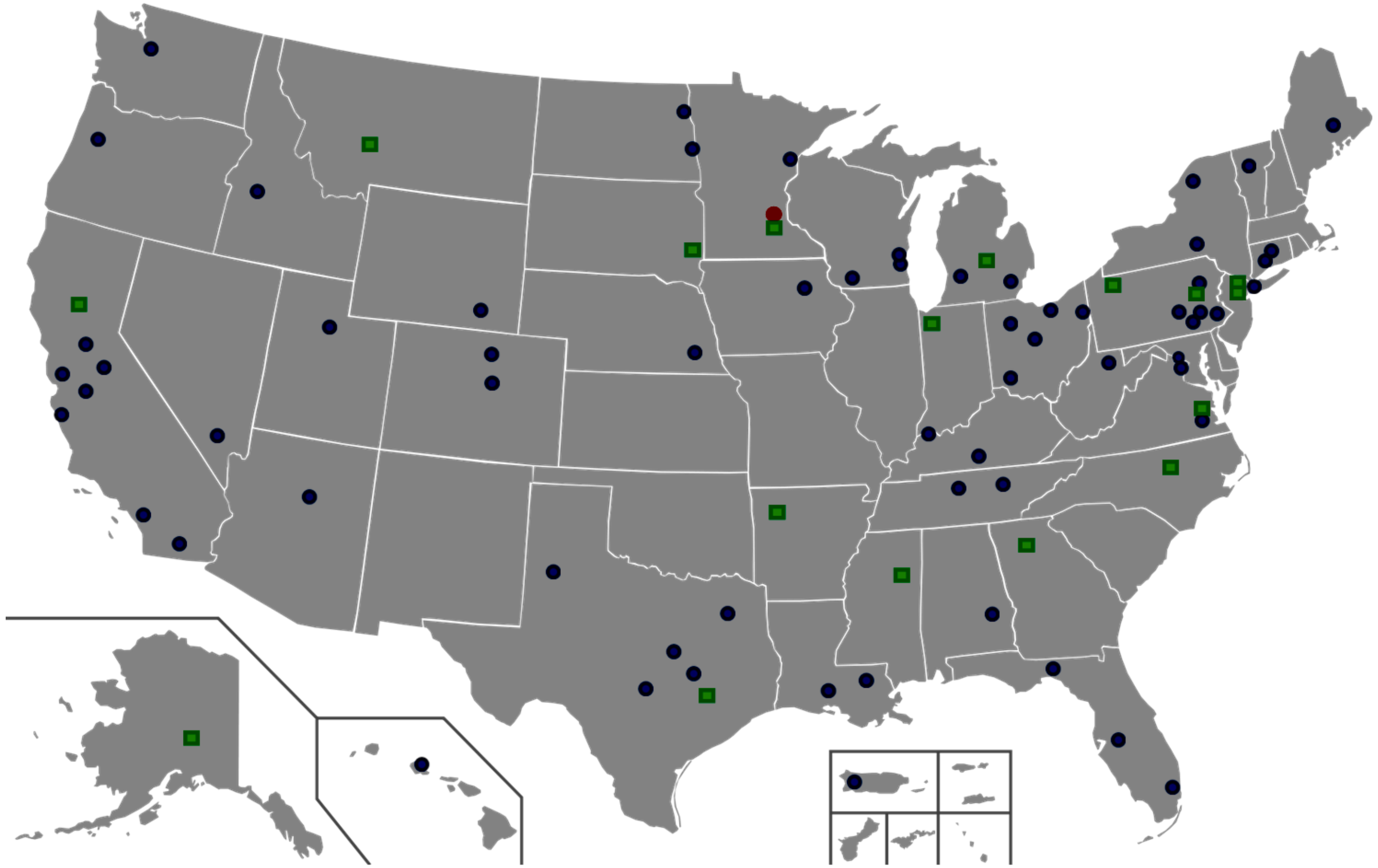
Defense

- Navy
- Air Force
- Army

Industrial Competitiveness

- Automation/Robotics/Advanced Manufacturing

"A Nationwide Consortium of Universities to Revitalize Electric Power Engineering"

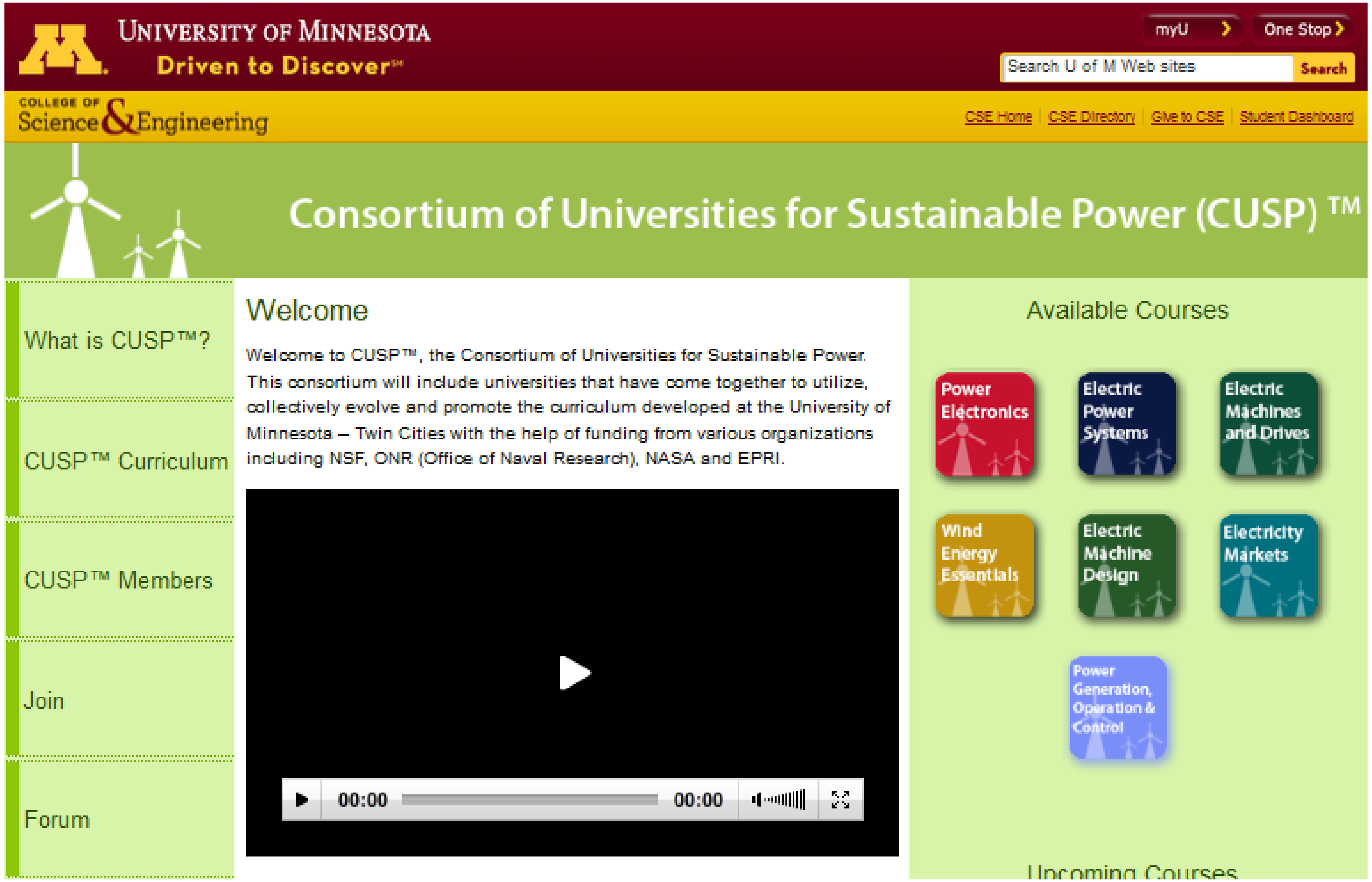


~ 80 Universities

"These schools represent about 25% of all the graduates in electrical engineering in in the U.S." – William P. Robbins

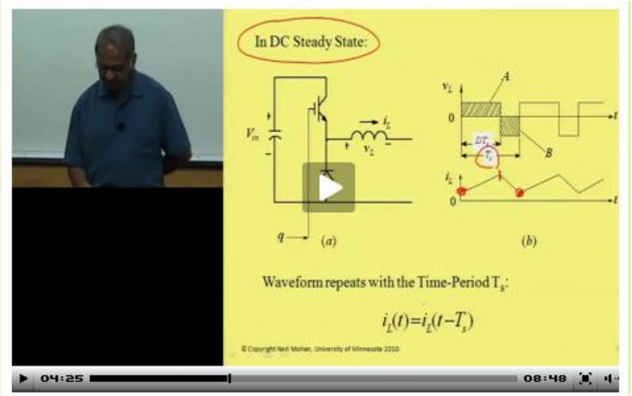
www.doeconsortium.ece.umn.edu

CUSP™



[WWW.CUSP.UMN.EDU](http://www.cusp.umn.edu)

Content of Each Course:



1. Video clips for each lecture:
2. Textbook (Reference Material)
3. In-class discussion problems
4. Labs
5. Homework Problems

Further Comments from PI Ned Mohan: Making Electricity from Renewables Cheaper Than Fossil Fuels in the Near-Term

- In spite of low oil and gas prices, the use of solar and wind to generate electricity is steadily increasing. However, the sure way to accelerate this growth dramatically is to make renewables cheaper than conventional sources. There is ample room for cost reduction in wind plants by reducing the nacelle weight on top of the tower by 20 percent, and in solar plants by reducing the overall system cost where solar cells now account for only one-third or less. This cost reduction can be accomplished by new and improved power-electronics-based interconnection of renewables (solar, wind, storage batteries) to the utility grid.
- In contrast to the conventional method based on the use of 60-Hz transformers, the proposed highly-modular interconnection will be lighter in weight by a factor of nearly **100** and hence much cheaper, reliable and more energy efficient. It should be noted that large-scale wind and solar plants are connected to the utility grid at the voltage level of **34.5 kV**, which has become the de facto standard voltage. However, the state-of-the-art power-electronics-based interconnection topologies are limited to **4.16 kV** voltage levels or below for various reasons. In contrast, our modular interconnection topology can be implemented at **34.5 kV** since it is derived from proven implementations in other applications at much higher voltages - as high as 200 kV.
- This represents *a breakthrough* and the recent Patent Office action gives us confidence that all our claims in the utility patent application filed by the University of Minnesota will be allowed. A great deal of research needs to be done with single-mindedly focus on this technological solution that we believe to be within reach and can be adopted worldwide <u>and</u> in near-term, given the urgency to combat climate change.

Real-time Ab-Initio Modeling of Electric Machines

Ali Davoudi, Taylor Johnson and David Levine
UT Arlington

NSF 1509804

2015-2018

Importance

- By 2030, electric machine will consume more than 13 quadrillion* watt-hours, annually.
  - Significantly reduced design cycle time for more efficient electric machines,
  - Realistic representation of machine-drive systems for smarter energy flow
  - co-simulation of temporally-diverse dynamic systems involving both the field equations and grid dynamics (e.g., wind farms).

- We ran a 2-D FEA simulation of an 8/6 switched reluctance machine using the commercial software MagNet 7.3 on a personal computer with Intel Core i7 CPU at 3.4 GHz. For 200 Hz excitation,

$$\alpha = \frac{\text{Elapsed simulation time}}{\text{Physical real time}} \approx 50,000$$

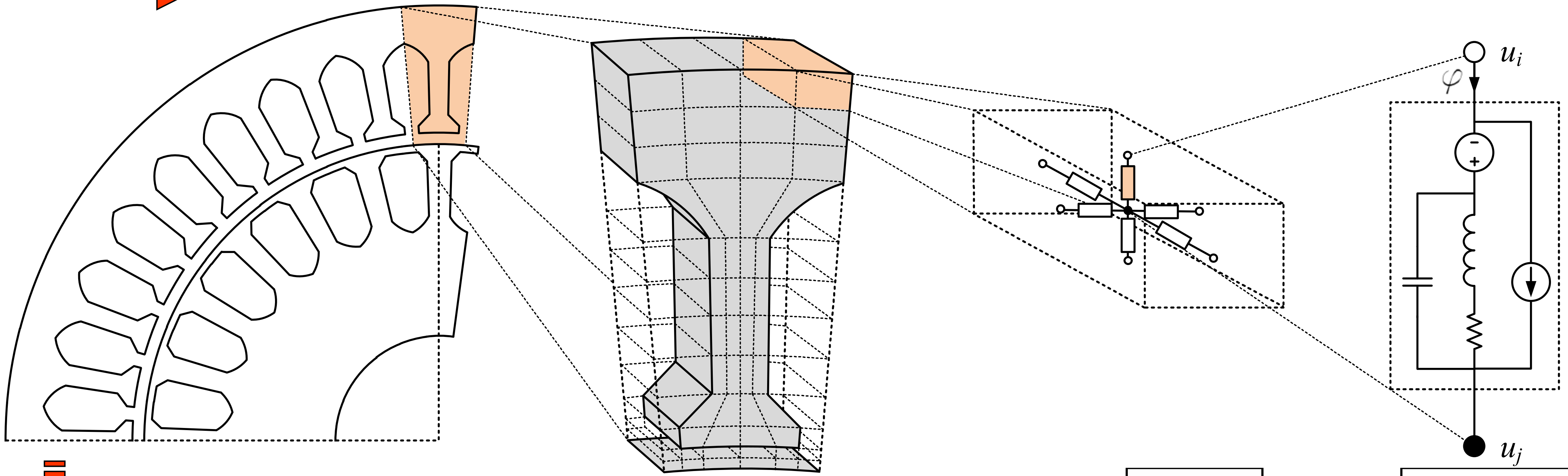
- **Using Moore's law, it will take decades to achieve $\alpha < 1$.**

- This is further aggravated when considering with high-frequency excitation (e.g., PWM inverters), more accurate tools (3-D FEA), or system-level studies (electric machines in renewable energy systems or electrified transportation fleets).

* One thousand trillions

3D+1 Accelerated Ab-initio Modeling of Electric Machines

High fidelity model development



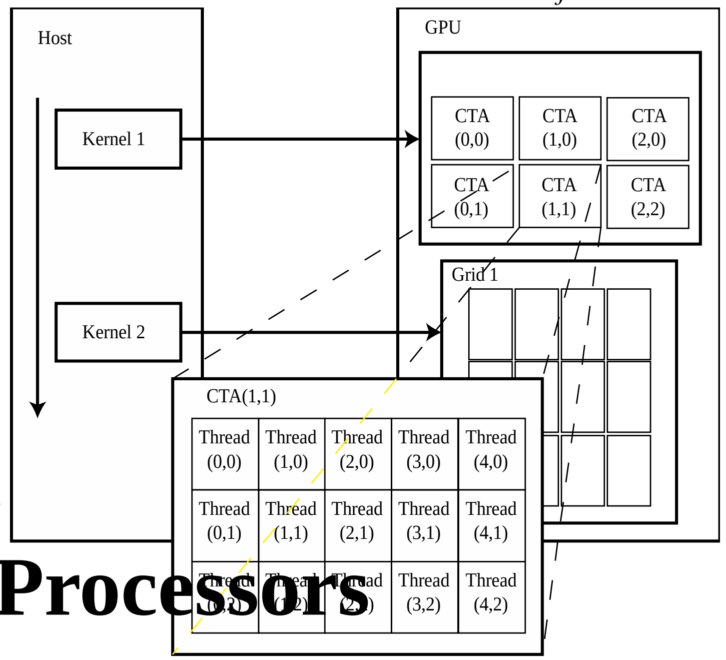
Model extraction

$$\frac{dx}{dt} = \begin{bmatrix} & & \\ & A & \\ & & \end{bmatrix} x(t)$$

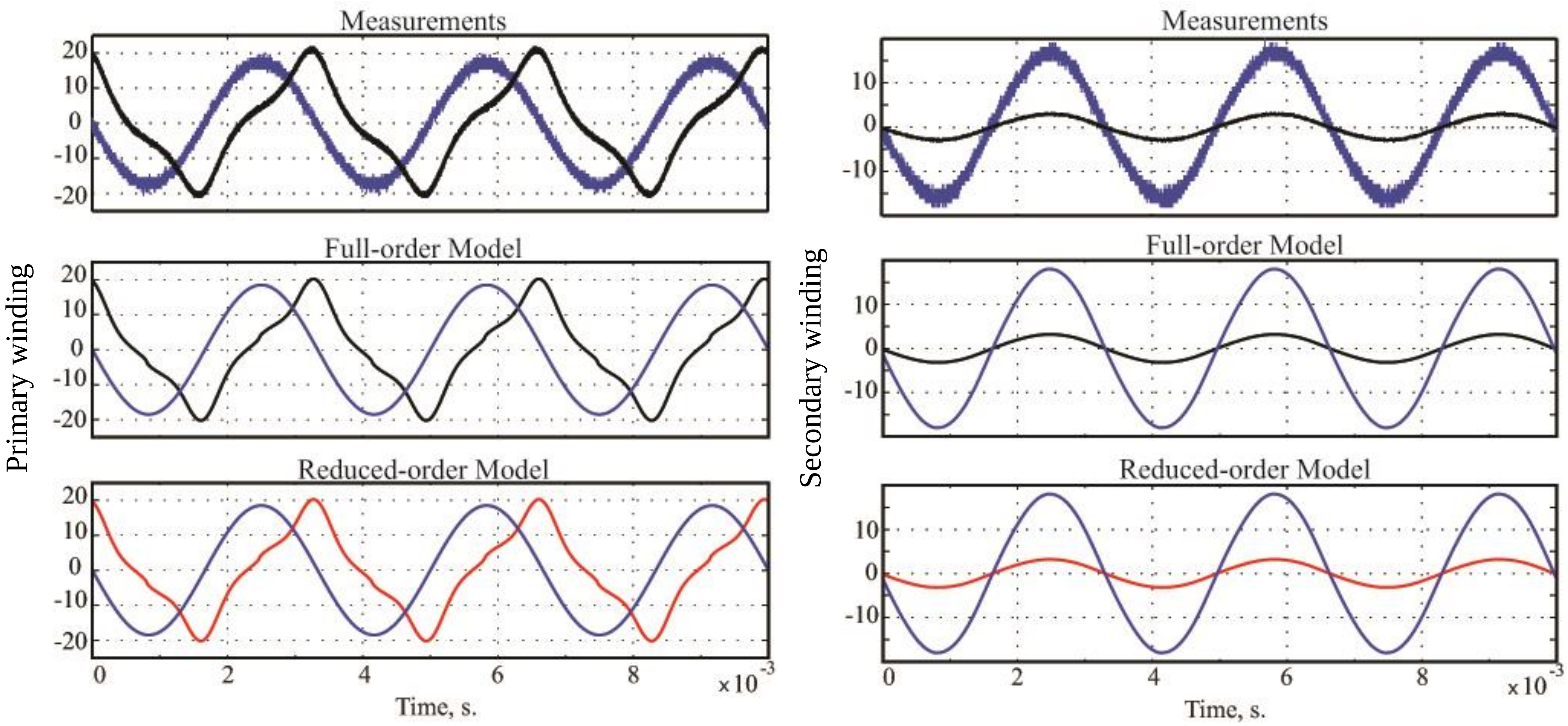
Order Reduction

$$\frac{d\hat{x}}{dt} = \begin{bmatrix} \hat{A} \end{bmatrix} \hat{x}(t)$$

Many Core Processors



Preliminary Experiments: Reduced-order Multiport Magnetic System



- Trajectory piecewise linear order reduction
- Going from 60 to 4 state variables for a high-fidelity transformer model
- **<u>500 X</u>** faster simulation

A. Davoudi, P. L. Chapman, and J. Jatskevich, "Reduced-order dynamic modeling of multiple-winding power electronic magnetic components," *IEEE Trans. Power Electronics*, 2012.

Basic Research Challenges

- **Breaking the compromise between modeling fidelity and simulation speed**
- Lacking proper reduction algorithms that are Computationally tractable; Accommodate different types of dynamic systems (nonlinear, time-varying); Preserve the essential dynamics of the original physical model.
- The reduction process is not a seamless task when large systems are concerned. Defining reduction metrics, final model order, and reversibility of the reduction process?
- Exploiting massively-parallel operations in many core processors for both the reduction process and the final reduced-order model implementations.
- Utilizing auto-tuning heuristics to exploit the maximum performance gain on hardware assisted simulators using the matrix properties in the matrix algebra and operation.

CAREER: Novel Integration of Fluid Dynamic Design into Electric Machines

Dr. Bulent Sarlioglu

Assistant Professor

Associate Director of WEMPEC

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WEMPEC

Wisconsin Electric Machines and Power Electronics Consortium

Integrated Compressor Machine

- This research investigates a novel electric machine where the rotor is shaped as an airfoil that achieves both motoring and compressor function
- Achieve self-cooling of the rotor and stator due to inherent gas flow, reduction in the axial length of the compressor, simpler and more robust mechanical design due to reduced axial length, and simpler bearing design due to reduced axial length
- Eliminate gearbox between electric machine and compressor to reduce the system complexity and improve the reliability
- Perform the multi-physics design in electromagnetic and thermal dynamic domains
- Improve the total system efficiency and reduce the cost

GOALI: A Novel Flux Switching Permanent Magnet Machine for Emerging and Renewable Energy Systems

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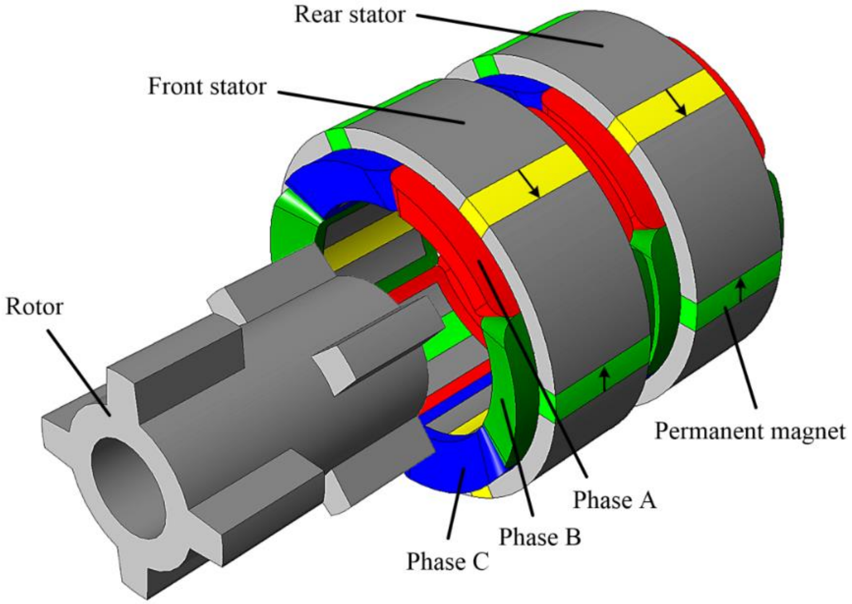
WEMPEC

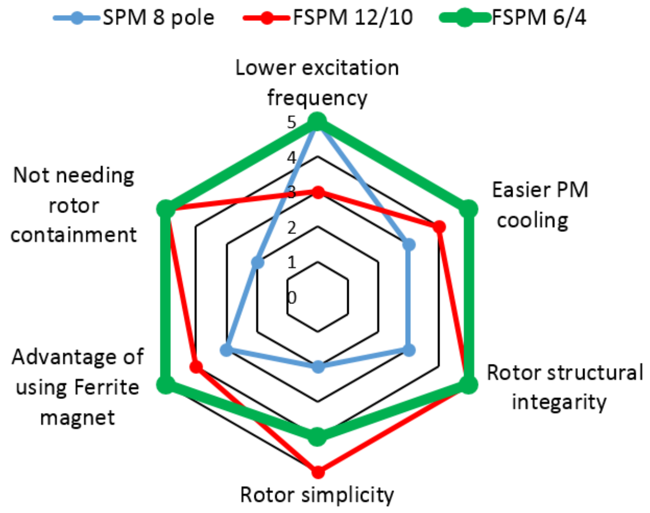
Wisconsin Electric Machines and Power Electronics Consortium

Proposed Dual-Stator 6/4 FSPM Machine

Motivation of Dual-Stator 6/4 FSPM Machine

- Requires 60% fundamental frequency reduction compared to baseline 12/10 FSPM machine
- Significantly reduce the harmonic distortions in the conventional 6/4 FSPM machine
- Achieves notably reduction of iron and magnet losses at high-speed condition
- Achieves lower inverter loss due to less required switching frequency
- Better rotor structure integrity, thermal regulation than surface PM machines at high-speed conditions
- Amenable for applications that require high torque density and high efficiency at high-speed conditions

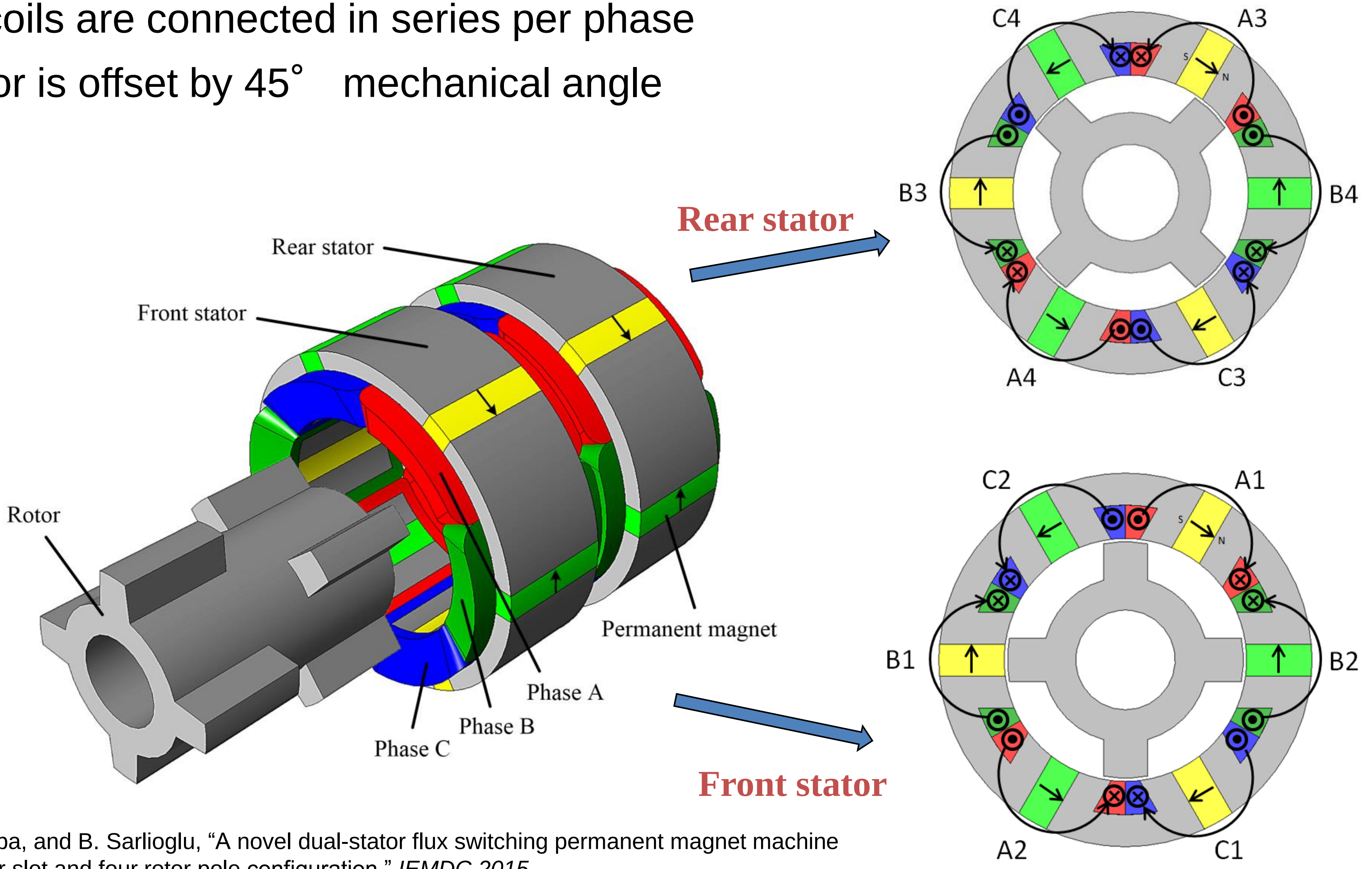




Structural Realization of Dual-Stator 6/4 FSPM Machine

Magnetic Structure Realization

- Windings directions are opposite in the two stators
- All coils are connected in series per phase
- Rotor is offset by 45° mechanical angle



Y. Li, D. Bobba, and B. Sarlioglu, "A novel dual-stator flux switching permanent magnet machine with six stator slot and four rotor pole configuration," *IEMDC 2015.*

Electrostatic Machines in Large Applications

Dan Ludois
Asst. Prof. ECE, UW-Madison
Associate Director, WEMPEC

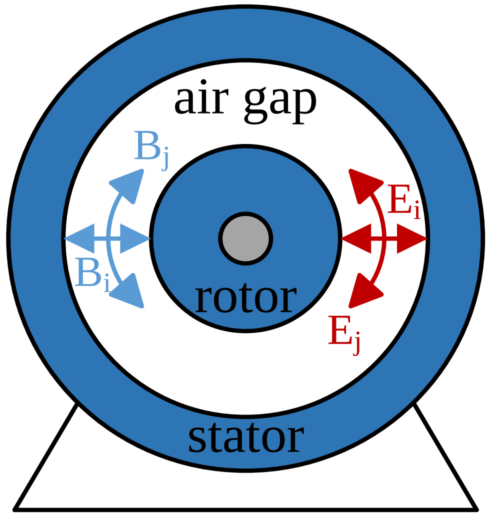
THE UNIVERSITY of WISCONSIN MADISON

March 2016

Funded by NSF CAREER Award

Electrostatic Machinery

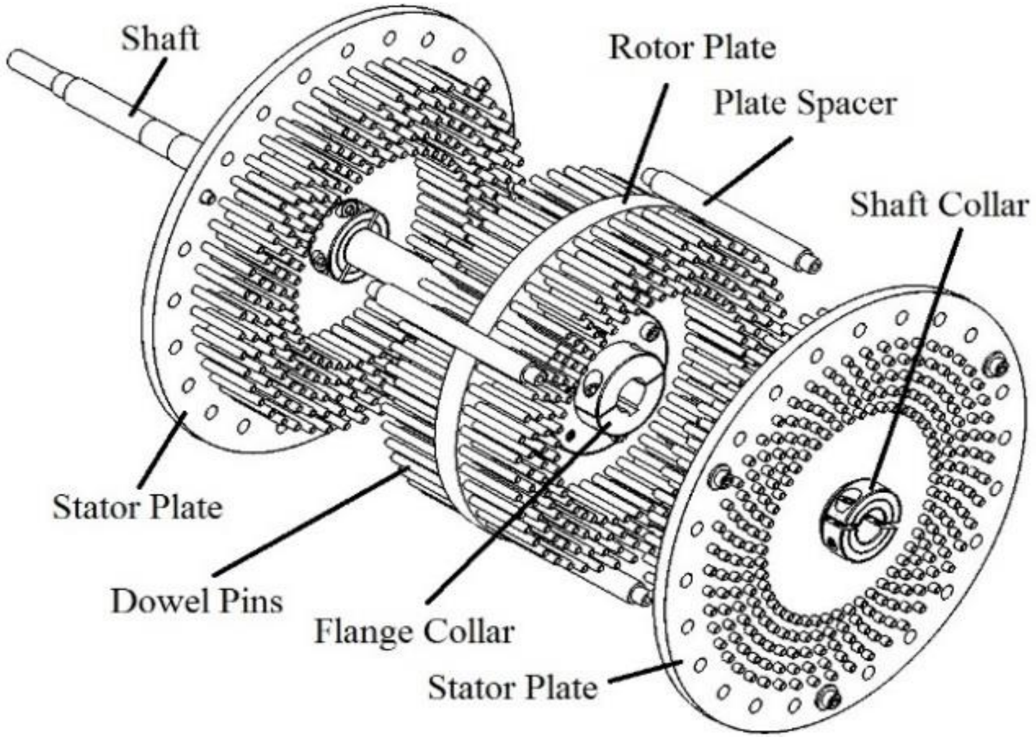
- Use Electric fields to make torque
  - Use electric fields acting on charge, rather than magnetic fields acting on currents
  - Voltage = torque, current = speed
  - No losses (ideally) for rated torque at stall since *i* = 0
- Electrostatics allows a fundamental materials change
  - No Iron, copper, windings, or magnets
  - Advanced manufacturing processes centered around dielectrics
    - Injection molding
    - 3D printing
    - Liquid dielectrics
    - Inherently operates at medium voltage
- Must get average air gap shear stress up!
  - In air, sm >> se, ~1000x
  - Displace air, fill machine with insulating dielectric fluid
  - Fluid provides 100x increase, (increased breakdown E and er)
  - Increased surface area remaining 10x
  - Intended for low speed direct drive given viscous losses

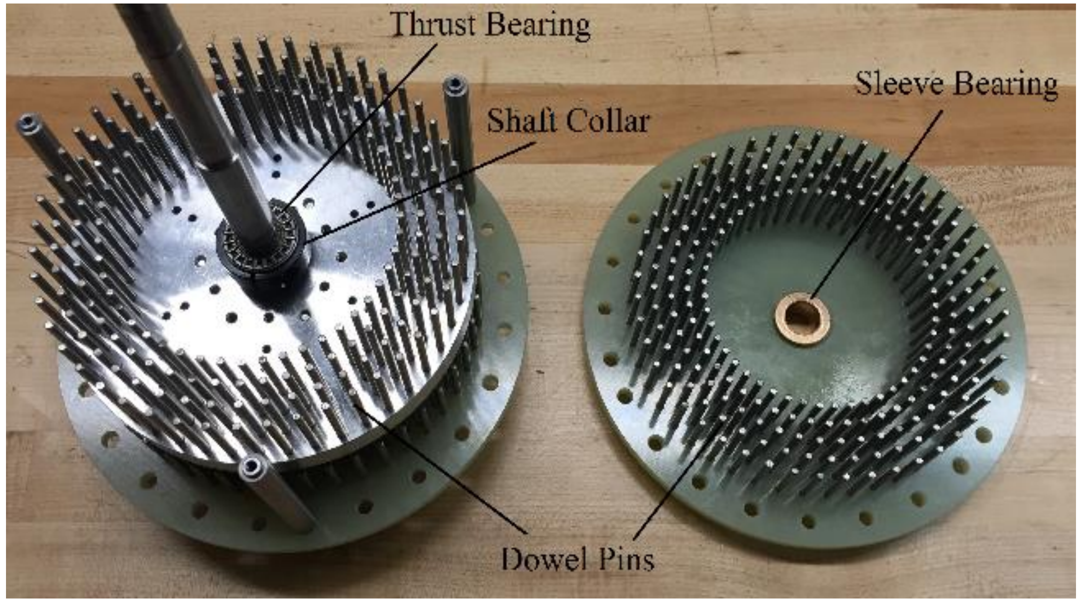


$$\sigma_e = \varepsilon_0 \varepsilon_r E_i E_j$$

$$\sigma_m = \frac{1}{\mu_0 \mu_r} B_i B_j$$

Prototype Electrostatic Machine





- Ge, B.; Ludois, D.C., "Design Concepts for a Fluid Filled 3-Phase Axial Peg Style Electrostatic Rotating Machine Utilizing Variable Elastance," in *Industry Applications, IEEE Transactions on, 2016 Available on IEEE Xplore Early Access doi: 10.1109/TIA.2016.2517075*
- Ge, B.; Ludois, D.C., "A 1-phase 48-pole axial peg style electrostatic rotating machine utilizing variable elastance*," in IEEE International Electric Machines & Drives Conference (IEMDC),* 2015 IEEE, pp.604-610, 10-13 May 2015 *Available on IEEE Xplore*
- Ge, Baoyun; Ludois, D.C., "Evaluation of dielectric fluids for macro-scale electrostatic actuators and machinery," *Energy Conversion Congress and Exposition (ECCE), 2014 IEEE* , pp.1457,1464, 14-18 Sept. 2014. *Available on IEEE Xplore*

Possible Large Scale Applications

- Large Direct Drive Machines
  - Low Speed, High Torque
  - Medium to High Voltage Operation
  - Wind, HVAC, heavy industry

Sculpting Electric Machines for Unidirectional Motion – Hypothesis

=

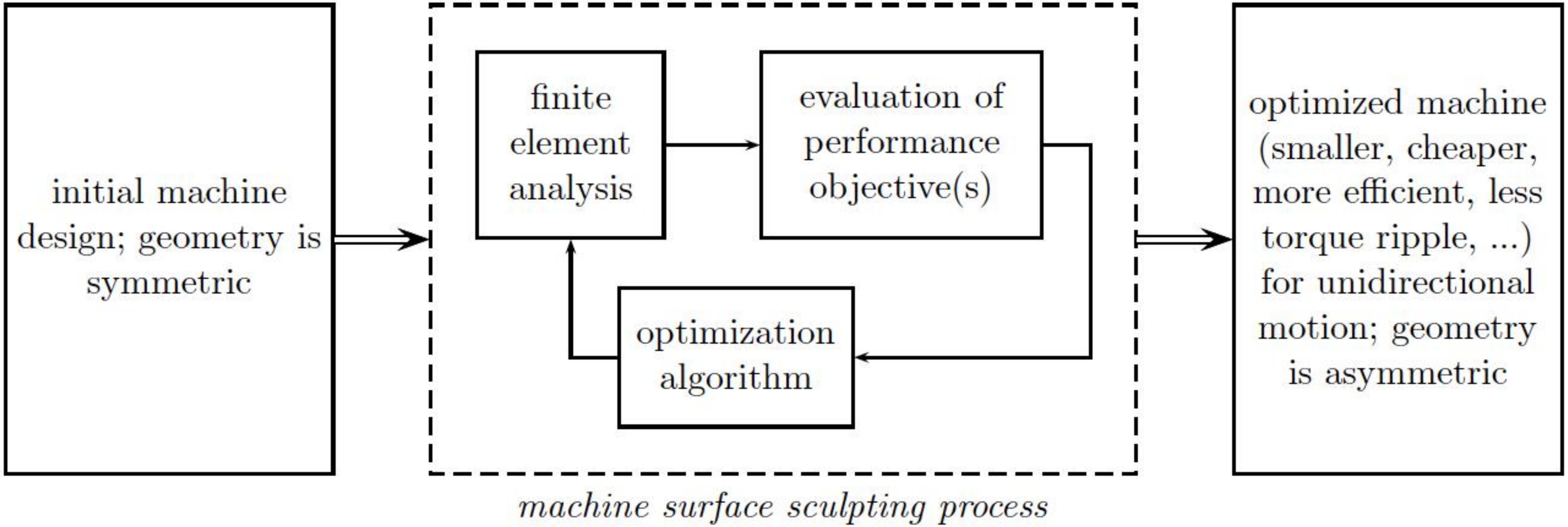
Dionysios Aliprantis, Purdue

The Charioteer of Delphi
(Heniokhos), 474 BC

This research

- Idea: *The vast majority of electric machines rotate in a single direction over the span of their lifetimes*
- Why not take this into account during design?
- Improved designs will lead to enhanced performance for a *preferred direction of torque generation*
- How to achieve: Precisely sculpt stator and rotor surfaces surrounding the air gap
- This leads to nonconventional asymmetric machine designs

Overview of design methodology



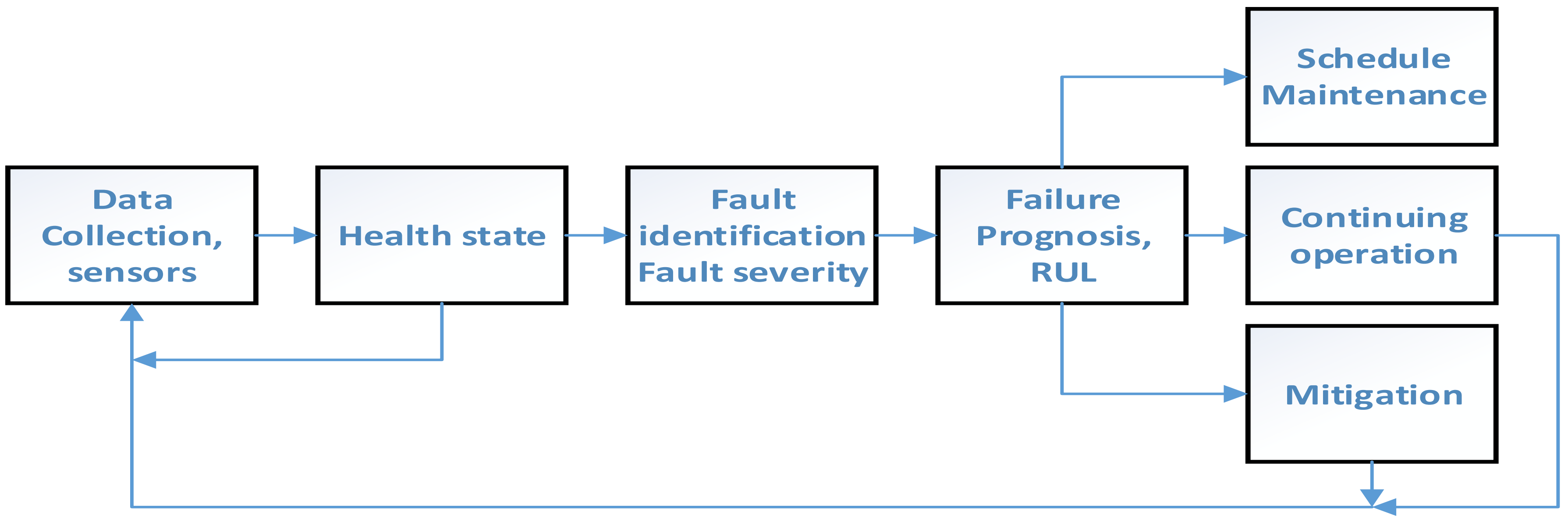
Application Example: A Switched Reluctance Machine Design for a Heavy Hybrid Vehicle

- Stator and rotor teeth are simultaneously sculpted
- Also, current waveforms are controlled (shaped) as well
- Multi-objective optimization problem formulation: For given electromagnetic torque level in both motoring and generating (regenerative braking) modes,
  - minimize rms of current (i.e., ohmic loss)
  - minimize torque ripple
- Results indicate potential to substantially improve (10-20%) the machine performance by smarter design

MSU-GM GOALI: Failure Diagnosis and Mitigation in Permanent Magnet AC Machines

PI: Elias Strangas, Michigan State University

- Identify faults using both model and data based methods with test bench validation,
- Faults include: stator (open and short circuits, power electronics), rotor (eccentricity, demagnetization) and bearings (due to aging and bearing currents),
- Prognosis based on published databases, trending, physical models,
- Mitigation when possible: change of topology, alternative control operation (e.g. field weakening, fewer phases), decrease of power level,
- Predict RUL (Remaining Useful Life) to accurately schedule maintenance interval, both with mitigation and without.

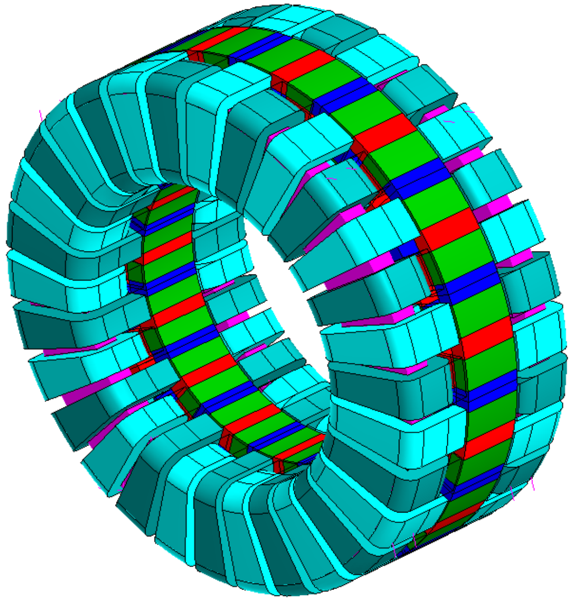


Direct-Drive Modular Transverse Flux Electric Machine without Using Rare-Earth Permanent Magnet Material

PI: Iqbal Husain, Co-PI: Srdjan Lukic

Graduate Students: Zhao Wan and Adeeb Ahmed

- Designing and building two high torque density direct drive Transverse Flux machines for direct drive high torque low speed applications, such as electric bikes, hub motors and small wind generators
- Modular design for ease of manufacturing and scalability for large machines
- Scalability study for large machines, especially large wind generators
- Design based on analytical models and FEA simulations, and includes electromagnetic, structural and thermal analysis



Magnetically Geared Renewable Energy Generators

ECCS 1408310 – Jonathan Bird – Portland State University

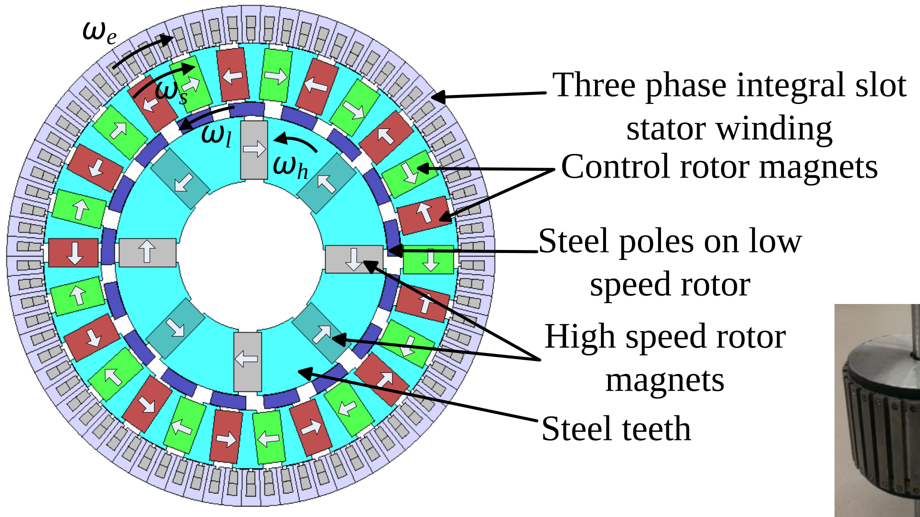
Magnetic Gearing:

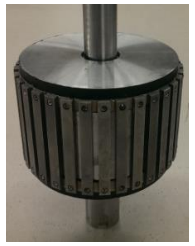
- Creates speed change without physical contact
- Has very high torque density (>250Nm/L)
- Magnetic gearbox can be integrated with a stator to create a magnetically geared generator
- Gearbox has inherent overload protection (poles slip rather than mechanically fail)

Challenges:

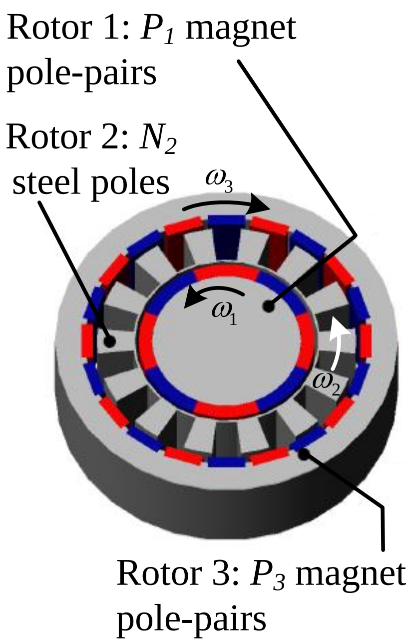
- Need to demonstrate that torque-per-kilogram of magnet material is competitive.
- Need to demonstrate robust manufacturable designs.

III. Continuously Variable Magnetic Gearbox





II. Basic Principle:



If the relationship between the steel poles is chosen to be

$$P_1 = |P_3 - N_2|$$

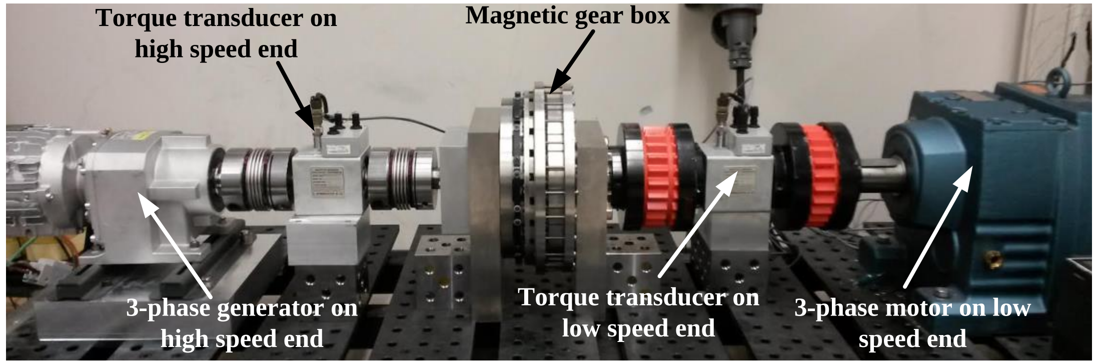
Speed relationship given by:

$$\omega_1 = \frac{P_3}{P_3 - N_2}\omega_3 + \frac{N_2}{N_2 - P_3}\omega_2$$

when ω_3=0, gear ratio:

$$\omega_1 = \left(\frac{N_2}{N_2 - P_3}\right)\omega_2$$

IV. Axial Magnetic Gearbox



World's highest volumetric torque density axial magnetic gearbox being tested on the test-stand. This axial magnetic gearbox will be modified and be used in a direct-drive wind generator test stand.

Thank you

Questions?