The Grainger Center for Electric Machinery and Electromechanics at the University of Illinois

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Introduction

- The Grainger CEME began operation in 1999.
- Became permanent in 2003.
- Perhaps the nation’s largest endowed *program* in an electrical engineering specialty area.
- Research leverages the broader program in power and energy systems.
- Emphasis on very long term fundamental advances.
Motivation

- Electric machines consume nearly 2/3 of all global electricity.
- They are nearly universal in electricity production.
- Major growth in transportation, in small portable devices, in wind and wave generation, . . .
- Many designs are old, both in the sense of predating computer tools and modern manufacturing methods, and in the sense of not making use of power electronics.
Design

• Magnetic machines:
  – Force density is $J \times B$.
  – For steel machines, $B$ is determined by saturation.
  – $J$ is thermally limited – copper current density.

• Some fundamental aspects are clear:
  – Wound-rotor synchronous machines can reach both limits and have stator cooling access.
  – Induction machines can also reach both limits, but rotor cooling is more limited.
  – Permanent magnet machines generally have lower flux limits.
  – Reluctance machines do not decouple the effects, so the force density is lower.
Design

- Future design has four key attributes:
  - Fast, accurate electromagnetic design that can be used repeatedly.
  - Incorporation of thermal and mechanical analysis.
  - Materials and manufacturing as design objectives rather than constraints.
  - System-level designs: controls and loads.
- In combination, these give crucial results:
  - Unlikely that one type of machine is universal
  - Power electronics and sensors are fundamental.
- Important to recognize that innovations in machines are not necessarily in industrial applications.
CEME and Predecessor Innovations

- Plug-in hybrid electric vehicle, on-board charger: 1994.
Sample Innovations

- Ripple correlation control
  - Extracts information from converter ripple signals
  - Use this information to drive toward an optimum (lowest loss, highest power delivery, etc.)

- Fabrication of inductors for monolithic converters
  - Plastic deformation process yields inductors with much higher Q than spiral planar constructions

Ripple correlation near MPP for solar application
Emerging Topics

- Transportation electrification
  - Drive reliability
  - “Appropriate control” for low-performance loads
  - Delivering extreme peak torques
  - Extensions to off-road, rail, aircraft, and other transportation modes

- Wind energy conversion
  - Comprehensive mechanical and electrical optimization.
  - Support wide operating ranges.
  - Reliability analysis.

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Advanced Power Semiconductors

- Compound materials emerging for power electronics applications.
- Silicon carbide is being commercialized.
- Gallium nitride has several advantages compared to SiC.
- Important in high temperature drive applications.
Materials

- Ferromagnetic materials for machines
  - Emerging Si steels with extreme silicon content
  - Single-crystal manufacturing
  - Nanostructured magnetic materials
- Heat transfer advances
  - Phase-change heat pipes
  - Immersion methods
  - Optimize total design
- Materials based on process objectives

Institute of Experimental Materials, Slovakia
Sample topic areas

- Analysis and control
- Design optimization
- Modeling and simulation

- Hybrid cars
- Electric ships
- High performance drives
- Efficiency optimization
Machine as Metamaterial

- Metamaterials are composites that achieve otherwise implausible properties.
- Example: induction machine rotor is a ferromagnetic and conductor composite intended to provide an otherwise unavailable combination of conductivity and permeability.
- The structure also achieves anisotropic conductivity.
Machine as Metamaterial

• Notice the implications for design:
  – Optimize material properties and geometry.
  – Then determine how to implement properties.

• Similar arguments for IPM and other machines.
High-Performance Converters

“Time-optimal” control

- “Digital switch” fast dc-dc converter control for µP loads.
- Efficiency enhancement for digital loads, data centers.
- Inverters that match the operating life of silicon PV panels.

Energy-based real-time digital control
Drive Control

- Low-sensitivity dynamic methods.
- Determine the impact of uncertainty.
- “Appropriate control.”
Collaborative Network

• The Grainger CEME leads a national collaborative network for machines research:
  – Berkeley
  – Georgia Tech
  – Oregon State
  – Ohio State
  – Purdue
  – Wisconsin
Collaboration on campus

- Electromagnetics (Computation)
- Control and Circuits (Low-power circuits, hybrid control)
- Computer Engineering, CS, and CSL (Smart Grid)
- Materials Science (Devices and solar energy)
- Chemical Engineering (Fuel cells and carbon reduction)
- New ECE building – the largest planned US net-zero-energy facility
Data Center Power

• Less than 50% of electric power into a modern data center is delivered to the integrated circuits that do the work.
• Efficiency is even lower when considered in terms of data processing per unit of energy.
• The relative losses increase closer to the circuit boards.
• Issues:
  – Chip-level power
  – Board-level power
  – Rack-level power
  – Building-level power
Opportunities

- Plug-in vehicle grid integration, market methods, and storage performance.
- "Reference designs" for machines.
- System-level analysis, design.

- Grid intelligence
- Motors with "power throttle" capability
- Power converter drive integration.
Smart Grid: Customer Choice

- The conventional grid decouples consumer choice and electricity supply.
- Several current, emerging, and future strategies to improve the situation:
  - Time-of-day price signals
  - Real-time control
  - Customer-based utility-interactive appliances
  - Intelligent real-time metering and monitoring
The Smart Grid

- General concept of extensive intelligence embedded in the electricity grid.
  - Two-way data exchange.
  - Load priority.
  - Distributed renewables.
- Methods to adjust and control capacity.
- Methods to give choices to the end user.

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ICSEG System Scope

- Wind
- Solar
- Firewalls
- PHEV/Storage

Smart Grid sandbox
- Flexible and modular
- Algorithms
- Computing
- Communication
- Control
- Trust

Main grid

communication
ICSEG Validation Approach

Smart Grid Properties

Smart Grid Technologies

Validation Technologies

Smart Grid Validation Facility