Laboratory for Electromagnetic and Electronic Systems

The mission of the Laboratory for Electromagnetic and Electronic Systems (LEES) is to be the focus for research and teaching in electric energy from its production through its processing to its utilization and, in electromechanics, from the macroscopic through the microscopic levels. Electric energy and electromechanics are defined broadly to include power systems monitoring and operation; automatic control; power electronics; high-voltage engineering; and conventional, continuum, and biological electromechanics. Much of the work of the laboratory is experimental, and industrial sponsorship represents a large fraction of the laboratory's support. The laboratory's professional staff consists of 8 faculty from Electrical Engineering and Computer Science (EECS), 1 principal research engineer, 1 principal research scientist, and approximately 50 graduate students. The laboratory faculty and most of the staff are heavily involved in both undergraduate and graduate teaching. Faculty from the departments of Mechanical Engineering (ME), Chemical Engineering, and Materials Science and Engineering are collaborators in many of the laboratory's programs, and there are extensive joint activities with the Microsystems Technology Laboratory, the Gas Turbine Laboratory, the Materials Processing Center, the Laboratory for Information and Decision Systems (LIDS), and the Harvard–MIT Division of Health Sciences and Technology (HST).

Automotive Electrical and Electronic Systems

Laboratory research on automotive electrical systems is funded principally by the MIT/Industry Consortium on Advanced Automotive Electrical/Electronic Components and Systems, directed by principal research scientist Dr. Thomas Keim. Further funding comes from a grant from the Sheila and Emmanuel Landsman Foundation. This year the consortium made a transition from research driven by 42-volt systems to research to make better automobiles with advanced use of electric power and control, without special reference to the voltage at which these functions are implemented.

The laboratory's work on advanced automotive alternators has progressed substantially over the last year. Professor David Perreault and Dr. Keim, working with postdoctoral associate Dr. Saichun Tang, have continued the development of a fully packaged high-power alternator with integrated power electronic controls. The feasibility of the design has been now been demonstrated under laboratory test conditions, and construction of the final vehicle-ready prototype is in progress. Professors Jeffrey Lang and Perreault, Dr. Keim, and graduate student Leandro Lorilla have developed new construction and control methods for the field windings of automotive Lundell alternators that promise significant improvements in alternator power density and transient control. These new methods are compatible with and complement the other advances in alternator design that have been made by the laboratory. Together, these advances promise to address some of the major challenges that have arisen in automotive power generation and control. This research has been the subject of a patent and two journal publications over the last year.

Professor Markus Zahn, Dr. Keim, and graduate student Matthew Mishrikey are studying means of detecting electrical arcs in automobiles. Graduate student Rupam

Shrivistava and Dr. Keim have proposed a cost-effective means to reliably clear faults between buses at different voltages in dual-voltage electrical systems. Research associate Dr. Richard Roth, senior research associate Dr. Frank Field (both of the Center for Technology, Policy, and Industrial Development), Dr. Keim, and graduate student Christopher Hardin have completed an evaluation of the incremental efficiency of electricity production in automobiles.

Professor John Kassakian, Dr. Keim, and graduate students Ivan Celanovic, Natalija Jovanovic, and Francis O'Sullivan are investigating engine-independent thermophotovoltaic power generation. The team has succeeded in designing and producing a frequency-selective photonic filter that can more than double the efficiency of the process. Excellent progress is being made in nanoscale patterning to produce a frequency-selective emitter, which can be used in conjunction with the filter to further improve efficiency.

Professors Kassakian and Joel Schindall and graduate student Alejandro Dominguez-Garcia are working on the critical reliability considerations that are evoked when X-by-wire systems (steer-by-wire, brake-by-wire, throttle-by-wire, etc.) are utilized for automotive control. Using steer-by-wire as a model, they have developed several reliability models. However, even a vanishingly small probability of failure, when multiplied by the billions of vehicle-hours on the road per year, yields an unacceptable result (and at the same time, the high parts reliability and redundancy requirements lead to unacceptable costs). To address this, they have proposed some independent backup actuator mechanisms. Initial modeling and characterization of these mechanisms suggest that they have the potential to make X-by-wire feasible in automotive applications.

Principal research engineer Dr. Chathan Cooke, Dr. Keim, and graduate students Joseph Stark and Vasanth Sarathy have initiated experimental studies of surface insulation resistance degradation in automotive printed circuits.

Professors Kassakian and Perreault, Dr. Keim, graduate students Tushar Parlikar and Yihui Qiu, and undergraduate Michael Seeman have substantially reduced the drive power requirement for the group's novel electromechanical valve actuator. A patent covering this actuator has been issued. This work is funded by the Sheila and Emmanuel Landsman Fund.

Modeling, Monitoring, and Control of Power Systems

Professor Steven Leeb has initiated two large research programs with the US Navy (in collaboration with faculty in Ocean Engineering) aimed at developing performance-based monitoring and control systems for the critical electromechanical elements of warships. They have developed a new system identification approach for determining the parameters of a differential equation model of a system from observed data but with no initial guess (a priori knowledge) of the parameters. During AY2004, preliminary diagnostic monitors were installed on several oceangoing vessels as test platforms. They have already demonstrated preemptive diagnostic monitoring capabilities, potentially providing the crews with the ability to detect faults in key systems such as HVAC and the steering gear before they become crippling.

Professor George Verghese, in collaboration with Professor Sandip Roy of Washington State University (who recently graduated from LEES), has continued his study of stochastic network models, originally motivated by efforts to represent cascading failures in power systems. His graduate students Carlos Gomez-Uribe and Arvind Jammalamadaka have examined how to estimate the evolving status of unobserved sites in a stochastic network from observations at other sites and how to make the required computations tractable by appropriate partitioning. Connections to the sort of probabilistic inference on networks that is considered in the expert systems/AI literature have been elucidated in Jammalamadaka's recent masters thesis, which also presented a valuable generalization of the "influence model" previously developed in this group.

In other work on general networks in Professor Verghese's group, graduate student Laura Zager is studying notions of graph similarity in domains such as biology, chemistry, power systems, and the web, and graduate student Victor Preciado is studying complex nonlinear networks, particularly issues of synchronization and chaos. Victor was selected this year for a summer course on complex systems at the Santa Fe Institute.

Professor Verghese and Dr. Bernard Lesieutre of Lawrence Berkeley Laboratories have been working with graduate student Ernst Scholtz to develop observers and observer-based fault detection schemes for the swing dynamics of power networks. A new graphically based design approach that they have worked out has proved to be very fruitful. They have also developed novel controllers that exploit the wave nature of (electromechanical) swing disturbances in power systems—for instance, zero-reflection controllers on boundary generators of the system or zero-transmission controllers on generators at nexus points of the network. Results of simulations on a reduced model of the important Western States Coordinating Council network that covers the western part of North America, as well as on a variety of other power system models, have been very encouraging; the group has recently given a high-visibility invited presentation of these results at the Stability Subcommittee meeting of the IEEE Power Engineering Society this year.

With graduate student Teruo Ono, on leave from Tokyo Electric Power Company to pursue his masters degree at MIT, Professor Verghese has also been examining the dynamics of competing adaptive agents in small power markets.

Working with graduate student Joe Stark, Dr. Cooke has developed a new high-voltage power source based on the structure of multiple Tesla coils operating in synchronism. This structure could be used to produce a directed energy system with low-voltage switching to create a phased array of high-voltage radio frequency (RF) energy. One application considered is for noncontact recharging of implanted medical devices.

Dr. Cooke, working with the electric power apparatus industry, has applied new ultrasonic diagnostics to quantify space charges in high-voltage epoxy dielectrics. This work has shown that there is a surprising amount of charge accumulations in what otherwise appear to be very uniform homogeneous materials. Such space charges are of importance because they can weaken a dielectric by local enhancement of stress. This effort is directed at improving the long-term reliability of materials for electric power systems and other high-voltage applications.

Power Electronics and Electromechanics

Professor Perreault and graduate student Timothy Neugebauer have continued their development of integrated electromagnetic filter elements. This year they developed a new low-cost construction method for integrated filter elements with inductance cancellation. These new integrated filter components provide factors of 10 to 30 increases in performance over conventional designs at virtually no increase in size or cost. This work was the subject of a patent disclosure and two journal publications this year.

A team of LEES researchers, led by Professor Perreault and including graduate student Juan Rivas, have continued development of new architectures and control methods for power electronics that enable dramatic increases in switching frequency. Such increases in frequency are needed to achieve major reductions in power converter size and cost. These new methods have now been demonstrated in prototype DC/DC converters running at 100 MHz, more than an order of magnitude higher than state-of-the-art commercial designs. In parallel with this effort, Professors Perreault and Lang are continuing the development of new types of power-passive components that scale well to small sizes and high frequencies. Advances this year include batch fabrication of integrated LC–passive components in both printed circuit and microfabrication technologies and their application in a radio-frequency power amplifier. Together these efforts have resulted in a provisional patent application and two publications this year.

With support from the National Renewable Energy Laboratory, Professor James Kirtley and graduate students Shiv Reddy, Andrew Thomas, and Colin Welting-Wu, with assistance from two UROP students, are constructing a novel hybrid generator, intended as a prototype for wind turbine use. The machine is a combination of a permanent magnet generator and a doubly fed (slip ring) machine. Construction of the machine is nearing completion and testing is to take place over the summer of 2004.

Sensors, Nanotechnology, and Microelectromechanical Systems

As part of the MIT Gas Turbine Engine Project, Professor Lang and graduate student J. Lodewyk Steyn, in collaboration with Professor Carol Livermore of ME and principal research engineer Dr. Steven Umans of EECS, have fabricated a set of electric microelectromechanical systems (MEMS) turbine generators that are designed to produce watt-level electrical power. This past year, tests to characterize one electric generator and demonstrate generation were successfully run; a power output of 0.2 mW was achieved. Tests at higher power levels are now underway. In parallel, Professor Lang, graduate student Sauparna Das, and colleagues from the Georgia Institute of Technology have fabricated similar magnetic MEMS turbine generators. This past year, tests to characterize one magnetic generator and demonstrate generation were also successfully run; a power output of 0.3 W was achieved. Tests at higher power levels are also now underway.

Professor Lang and graduate student Stephen Hou, in collaboration with Professor Alex Slocum of ME, have designed, fabricated, and demonstrated MEMS electromagnetic cavity resonators with a Q in excess of 100 and a center frequency that is tunable from 2.5 GHz to 4 GHz, for example. Work is now underway to build these resonators into RF communication systems.

Professor Zahn and his students have continued their research on the nanotechnology applications of magnetic fluids. They have discovered new spiral flows and droplet patterns forming very interesting images. Because of the striking nature of these images, they have been published worldwide in such places as *Wiedza I Zycie* (Poland), *MIT Technology Review, Science Central News, Suddeutsche Zietung* (Germany's largest newspaper), *Popular Mechanics,* and the *Journal of Visualization.*

Enhanced Ultracapacitor Analysis and Development

Professors Kassakian and Joel Schindall have been investigating an energy storage device called a double-layer capacitor (DLC) or ultracapacitor. By using an activated carbon coating to increase the electrode surface area, combined with an electrolyte having ions small enough to permeate the carbon pores and at the same time reduce the effective electrode spacing to half an ion diameter (about 7 angstroms), DLC energy storage density is several orders of magnitude higher than the best electrolytic capacitors. This is still one to two orders of magnitude less than a chemical battery. However, since the energy is stored as an electric field rather than through a chemical change of state, ultracapacitors can provide almost unlimited charge-discharge cycles, very high power density, and very little low-temperature degradation. As a result, ultracapacitors offer excellent potential to supplement batteries for the regenerative energy storage required in modern high-efficiency automobiles (plus a wide variety of other applications).

A recently completed MS thesis by David New has validated our understanding of the physical mechanisms associated with DLC energy storage. However, it has also confirmed significant limitations associated with ionic diffusion rate, conductivity, and chemical reactivity of the activated carbon lattice. As part of a planned PhD thesis by Riccardo Signorelli, we are now working to synthesize a structure where the activated carbon electrode coating is replaced with an ordered array of vertically aligned single-walled carbon nanotubes. Other researchers have proposed such arrays for other purposes, or have utilized a less efficient tangled nanotube structure, but we believe that our use of catalytically stimulated ordered growth will offer superior performance. Our calculations indicate that implementing the DLC electric field storage at nanotube dimensions will provide an increase up to two orders of magnitude in effective electrode surface area, while providing a uniform tube spacing that is well matched to the diameter of the electrolyte ions. This results in a predicted energy storage density (>150 Wh/kg) that is higher than any type of battery and comparable to fuel cells. In addition, the low contact resistance between active layer and current collector, combined with the ballistic transport exhibited by the nanotubes in the electrode structure, results in a predicted power density more than two orders of magnitude higher (>100 kW/kg) than either batteries or fuel cells.

From Bioelectromechanics to Biomedicine

Although LEES was heavily involved at one time in research into bioelectromechanics, that research has migrated to other parts of MIT over the past decade. However, some nascent research in Professor Verghese's group, carried out in collaboration with Professor Roger Mark of HST and Professor Peter Szolovits of EECS under a new National Institutes of Health grant, addresses model-based data integration and reasoning for patients in intensive care units. The LEES part of this work involves working with electrical circuit analogs for cardiovascular dynamics, addressing issues of modeling, model simplification, and identification. Graduate students Zaid Samar and Carlos Renjifo are working on data analysis and filtering, dynamic simulation, and model identification, while Tushar Parlikar is focusing on developing averaged models along lines that are evocative of yet different than those pursued in power electronics in earlier work of Professor Verghese's.

Some explorations in bioinformatics are also being carried out by Professor Verghese's graduate student, Keyuan Xu, in collaboration with Professor Sanjoy Mitter of LIDS.

Honors and Awards

Professor Perreault and doctoral student Joshua Phinney received an IEEE Power Electronics Society Transactions Prize Paper Award for their paper "Filters with Active Tuning for Power Applications."

John G. Kassakian
Director
Professor of Electrical Engineering

More information about the Laboratory for Electromagnetic and Electronic Systems can be found on the web at http://lees.mit.edu/lees/.