Laboratory for Electromagnetic and Electronic Systems

The Laboratory for Electromagnetic and Electronic Systems (LEES) applies a broad range of advanced technologies to increase the efficiency of electric energy production, distribution, conversion, utilization, and storage. It performs research in electromechanics from the nanoscopic to the macroscopic levels. Electric energy and electromechanics are defined broadly to include power systems design, monitoring, and operation; electrical energy storage; automatic control; power electronics; high-voltage engineering; and conventional, continuum, and biological electromechanics. In recent years, the laboratory has extended its expertise in control and monitoring of complex electrical distribution networks to the area of control and monitoring of complex patient monitoring systems such as in a hospital intensive care unit—a new area of research that offers considerable promise and has recently brought in funding from the National Institutes of Health (NIH).

LEES also maintains and operates a 3.5-MeV Van de Graaff electron accelerator, which has been used for cancer therapy and to develop hip replacement materials and is now used for cargo inspection research through nuclear resonance (funded by Department of Homeland Security through Passport Corporation), for basic studies of conduction in insulators (funded by Toshiba), and for radiation testing of commercial satellites.

Much of the work of the laboratory is experimental, and industrial sponsorship represents a large fraction of its support. The laboratory's professional staff consists of eight faculty members from the Department of Electrical Engineering and Computer Science (EECS), one faculty member from Mechanical Engineering, one principal research engineer, two principal research scientists, two postdoctoral associates, and approximately 50 graduate students. The laboratory faculty and most of the staff are heavily involved in teaching and course development, including outreach through freshman seminars and women's and minority programs. Two faculty are involved in managing the EECS VI-A Internship Program, and one faculty is codirector of the Bernard M. Gordon–MIT Engineering Leadership Program. Faculty from the Departments of Mechanical Engineering, Chemical Engineering, Materials Science and Engineering, Physics, and Architecture collaborate in many of the laboratory's programs, and there are extensive joint activities with the Microsystems Technology Laboratories (MTL), the Gas Turbine Laboratory, the Materials Processing Center, the Research Laboratory of Electronics (RLE), and the Harvard–MIT Division of Health Sciences and Technology (HST). Undergraduate students in LEES carry out a substantial number of Undergraduate Research Opportunities Program (UROP) and senior projects every term.

Automotive Consortium

For more than 10 years, LEES has hosted an automotive consortium to explore improved automobile performance through electronics. In November 2008, the MIT/Industry Consortium on Advanced Automotive Electrical/Electronic Components and Systems, jointly with the Sloan Automotive Laboratory, organized and hosted a conference in Cambridge on hybrid electric automobiles attended by automakers from three continents.

However, the declining fortunes of the automobile industry have resulted in a steady decline in consortium membership. The result was that as the year progressed, very few member companies elected to renew their membership, and we have dropped below critical mass.

As a result, we will conclude the activities of the present consortium over the next few months. In search of other opportunities, we intend to develop a proposal for a revitalized consortium with a revised mission and to promote this new research collaboration among previous consortium members. In addition, Dr. Thomas Keim, director of the consortium, has been studying and developing research proposals in the areas of advanced hybrid electric vehicles and plug-in hybrid electric vehicles.

Research Emphasis

LEES research emphasis has broadened from traditional applications of electrical power and energy and now includes several exciting nontraditional and cross-disciplinary areas that show great promise. In particular, many projects described here relate to the pressing topic of increased efficiency in electrical power generation and storage.

Representative LEES Energy-Related Projects

1. Nanotube-enhanced ultracapacitor (synthetic battery) for portable electrical energy storage
2. High-efficiency thermophotovoltaic energy conversion using photonics (heat to electricity)
3. Miniature gas turbine generators (in conjunction with Digital Avionics Systems)
4. Scavenging (reclaiming) vibrational energy
5. High-frequency (light-weight) DC–DC conversion
6. High-efficiency DC–DC conversion
7. High-efficiency windmill generator and ship propulsion
8. Electromagnetically actuated valves for internal combustion engines
9. High-efficiency automobile alternator
10. Design and monitoring of high-efficiency buildings (in conjunction with Architecture)
11. Nanofluids for efficient cooling and improved electrical breakdown characteristics in high-voltage electrical transformers
12. Research on breakdown mechanisms in high-voltage electrical insulators

In addition, the MIT Energy Initiative (MITEI) is preparing to launch a faculty-led interdisciplinary study that will examine the substantial issues surrounding the national initiative to enhance the functionality and reliability of the electric grid. Professor John Kassakian of LEES and professor Richard Schmalensee of the Sloan School of Management will lead the study. In addition to Professor Kassakian, four of the eight participating faculty are present or former members (and graduates!) of LEES.

Research Projects

Very-High-Frequency Electronic Power Conversion

Increasing the switching frequency of power electronics is a principal means for improving size and transient performance and for achieving higher degrees of integration. Professor David Perreault and graduate students Yehui Han, Anthony Sagneri, Jackie Hu, and Justin Burkhart have continued the development of power-conversion circuits that operate at very high frequencies (VHF) (30–300 MHz), two orders of magnitude higher than conventional designs. Recent advances by the group in this area encompass new circuit topologies, characterization of magnetic materials for radio frequency power operation, optimization and characterization of integrated circuit transistor designs for VHF operation, and development of design codes for integrated VHF transformers. Use of VHF converter technology is being pursued in a variety of applications and power levels, including miniature integrated power supplies. Efforts by the group in this area have resulted in several journal and conference publications this year, along with invited presentations on this topic, including a plenary talk at the Institute for Electrical and Electronic Engineering's Applied Power Electronics Conference and an invited presentation at the International Workshop on Power Supply on Chip.

Ultra-High-Efficiency Power Convertors

Professor Perreault, doctoral student Brandon Pierquet, and master's degree students Alex Hayman and Alex Trubitsyn have continued development of single-phase utility-interface power converters that operate at ultra-high efficiencies (>97%). This year, they developed first-generation designs of "microinverters" to interface low-voltage solar panels to the grid at ultra-high efficiency.

Very-Low-Voltage Power Convertors

The ongoing proliferation of electronic systems operating at very low voltages (~1 V) under precisely controlled conditions represents a challenge for both power regulation and distribution and has created a need for ultra-miniature power supplies capable of providing substantial voltage transformation along with high-bandwidth regulation. Professor David Perreault and doctoral students David Giuliano and Robert Pilawa have been developing two-stage architectures for low-voltage power conversion. This year they completed designs of appropriate integrated circuits and are in the process of taping out first-generation integrated circuits for this purpose. Professor Perreault, along with doctoral students Robert Pilawa and Wei Li, began applying some of these low-voltage architectural ideas to photovoltaic and thermophotovoltaic systems.

Electric Power Generation and Distribution

Professor James Kirtley is involved in renewable generation (chiefly wind) to electric power systems, mostly through the use of load adaptive control, and is working to understand how to use microgrids to improve electric power distribution reliability. In connection with the MIT Portugal Program, he is working with a graduate student to develop frequency-based load adaptive control to make power systems work better, particularly with fluctuating, nondispatchable sources such as wind. For the Masdar Institute of Science and Technology, he is collaborating with two faculty members to better understand the dynamics of islanding and islanding detection and the impact of renewable energy sources on tariffs in a deregulated system.

Direct Drive Turbines and Generators

Professor Kirtley is also involved in analyzing and designing direct-drive large wind turbine systems and generators. He recently completed an analytical and experimental project to better understand how stray load losses arise in induction motors. As part of the Electric Ship Research and Development Consortium, funded by the Office of Naval Research, he is helping to design improved propulsion motors for ships and to develop an architectural model for ship electric power systems.

Energy Conservation and Control ("No Watt Left Behind")

During the past year, Professor Leeb and his group received a $1.5 million grant over the next five years from the Grainger Foundation in support of the "No Watt Left Behind" initiative. This wide-ranging program is aimed at developing fresh technologies for energy and utility conservation and control for both new and retrofit applications in buildings and transportation systems. During the performance period, Professor Leeb's group has demonstrated, for the first time, the proximity detection of building occupants around solid-state light-emitting diode lighting by inexpensively detecting the small changes people make in the electric fields around a lamp. Additional efforts over the next five years, begun during the past year, will be directed at new "smart metering" technologies for tracking electrical, water, and gas consumption and for providing intelligent price-based controls for utility customers, using noninvasive sensing methods.

Diagnostic Load Voltage Transient Monitoring for Electromechanical Systems

During the past year, Professor Leeb's group conducted field experiments with diagnostic monitoring for electromechanical systems. They have demonstrated the first real-time noninvasive load monitoring that has provided extremely useful diagnostic information to a military crew on board the US Coast Guard Cutter Escanaba.

Professor Leeb's group also conducted diagnostic monitoring and prognostic experiments for heating, ventilation, and air conditioning (HVAC) units in the field this year in Massachusetts and North Carolina. Field surveys have shown that approximately 50% of the HVAC units operating in the field are broken in ways that do not halt operating but that do waste tremendous amounts of energy. The power monitors tested this year identify these faults quickly and inexpensively.

Implantable Electroencephalogram Integrated Circuit Development

During the past year, Medtronic has worked with Professor Leeb's group to develop a new implantable electroencephalogram integrated circuit for medical research and therapy. Preliminary data were successfully collected from a live-animal experiment. The circuit was "taped out" as an integrated circuit that will be tested during summer 2009.

Microelectrical Relay Development

Professors Lang and Slocum (Mechanical Engineering), with graduate student Alexis Weber, have completed the development of galvanically isolated microelectromechanical system (MEMS) relays capable of hot-switching electric power at voltages up to 1 kV and 3 A. The relays exhibit sub-ohm contact resistance and have been run for more than 10^5 cycles without signs of mechanical fatigue. Their power-handling capabilities are extremely high for a MEMS relay. The applications for these relays range from power handling in equipment to power handling in residential settings.

Microenergy Harvesters

Professor Lang, research staff David Otten, graduate student Samuel Chang, and undergraduate student Frank Yaul are developing devices to harvest electrical energy from the vibration of a moth as it flies. To date, they have demonstrated bench-top harvesting of approximately 1 mW using a system light enough for flight. This work is part of a multiuniversity project to demonstrate the successful integration of electronics with the nervous system of an animal.

Integrated MEMS Pressure Sensor Arrays

Inspired by the lateral line organ in fish, Professors Lang, Hover (Mechanical Engineering), and Triantafyllou (Mechanical Engineering), with graduate students Stephen Hou and Vincente Fernandez, are developing large arrays of MEMS pressure sensors, and the attendant signal-processing algorithms, for use in the passive navigation of underwater vehicles. To date, they have demonstrated functional single-cell pressure sensors and are now duplicating them on a large scale. They have also demonstrated pressure signal-processing algorithms that can detect and classify distant objects based on the pressure date measured from a sensor array.

High-Density Heat Sinks

Professors Lang, Brisson (Mechanical Engineering), and Wang (Mechanical Engineering), with graduate student David Jenicek and many others, are just now beginning the development of very-high-density heat sinks for cooling electronics. This work is to meet a Defense Advanced Research Projects Agency challenge in which 1 kW of heat is delivered from a 50 C rise to air in a 4-inch-cube heat sink using only 30 W of active power. The resulting coefficient of performance of 33 is extremely high for a physically small heat sink.

Large-Scale Magnetics for Surgical Assembly

Professor Lang and postdoctoral researcher Padraig Cantillon-Murphy are beginning to explore the use of magnetics in gastrointestinal surgery. This work is performed in collaboration with doctors at the Brigham and Women's Hospital. The objective is to improve the reliability and greatly reduce the time of the surgeries.

Stress-Induced Charge Transport at Insulator-Metal Interfaces

Dr. Cooke, working closely with industry, has focused research on the reliability of electric insulation and the large impact of charges at electrode-insulator interfaces as a principle mechanism for excess stress and failure. New ultrasonic diagnostic studies reveal intense near-surface dipole charges that need to be controlled to achieve improved reliability.

The future work of Dr. Cooke will be directed at five research topics: (1) higher-resolution charge detection by shorter-pulse ultrasound methods to reveal the mechanism of charge transport at metal-insulator junctions, (2) the role of space charges in oil as a cause of premature failures in power transformers, (3) the impact of filler size down to nanodimension on charge transport in solid dielectrics, (4) ultra-short pulse measurement for failure detection in power transmission cables, and (5) improved radiation control and diagnostics for the electron beam facility to improve single-event electron counting.

Electron Beam Accelerator Studies

Dr. Cooke has introduced upgrades to the performance of the LEES 3.5-MeV electron beam accelerator by improvements to the beam-handling systems. The accelerator facility is used in a variety of irradiation experiments with energetic electrons and gamma rays, including charge implantation and dose distributions in dielectrics, polymer processing for biocompatible hip and knee replacement materials, contact lens materials, physics studies of nuclear fluorescence for cargo container inspection, and satellite sensor development and calibration for solar flare detection.

Nanotube-Enhanced Ultracapacitors for Improved Electrical Energy Storage

The goal of this project, conducted by professors Joel Schindall and John Kassakian and graduate students Riccardo Signorelli (PhD June 2009) and Daniel Ku (SM 2009), with assistance from professor Donald Sadoway (Materials Science and Engineering) and Institute Professor Mildred Dresselhaus, is to develop a practical electrical energy storage device that combines the long life and rapid charge–discharge capability of a capacitor with the much higher energy storage capacity of a rechargeable battery. The approach is to increase the energy storage capacity of a commercial electrical energy storage device, called a double-layer capacitor or ultracapacitor, by replacing the activated carbon electrode coating with an array of vertically aligned nanotubes. Calculations indicate that this structure could achieve an energy storage density approaching that of a lithium battery, while providing significantly higher power, faster recharge, and almost unlimited lifetime even with deep-cycle operation.

The group has successfully fabricated electrode material by using a reactor designed and assembled in LEES, has assembled working test cells that confirm ultracapacitor performance, and has recently achieved storage densities several times greater than today's commercial ultracapacitors.

Behavior of Materials in High Electromagnetic Fields

Professor Markus Zahn's research focus concerns electromagnetic fields and media with applications to dielectric physics and high-voltage breakdown in gases, liquids, and solids; electrohydrodynamics and ferrohydrodynamics; and the development and application of dielectrometry and magnetometry sensors for nondestructive testing and measurements of dielectric, conduction, and magnetic properties of media.

Streamer Propagation and Electrical Breakdown in Nanofluid Insulating Oil

This project, sponsored by the ABB Group and conducted by Professor Zahn and PhD student George Hwang, concerns the use of transformer oil-based nanofluids that use conductive nanoparticle-sized suspensions to increase the breakdown voltage and to slow down positive breakdown streamer propagation in transformer oil. The recent focus of this project concerns the role of pressboard cellulose material immersed in transformer oil and transformer oil nanofluids on electrical breakdown streamers.

Dielectric Materials for Advanced Applications

An intensive theoretical and experimental program to increase the electrical breakdown strength of dielectric materials and electrode structures for use in advanced electric power systems, biomedical technologies, and other high-voltage applications has been funded by Siemens. Vacuum, gaseous, liquid, and solid dielectrics will be studied and tested for ways to increase their present voltage and electric field limits without electrical breakdown. It is proposed to increase the breakdown strength for practical applications by using electrodes where the positive electrode injects positive space charge while the negative electrode injects negative space charge. Such a bipolar homocharge configuration has been shown by Professor Zahn's past work to decrease the probability of electrical breakdown, as space charge shielding reduces the electric field at the electrode surface.

Magnetic Fluids

The Binational Science Foundation supports a microfluidics project studying the behavior of particle suspensions of magnetic material known as magnetic fluids or ferrofluids and of dielectric particle suspensions in dielectric fluids. PhD student Shahriar Khushrushahi is working with Professor Zahn in studying ferrofluid flows excited by rotating magnetic fields. Hsin-Fu Huang is working with Professor Zahn on "Quincke electrorotation" using an insulating dielectric particle suspension in more conducting liquids. When an electric field is applied above a critical strength, the dielectric particles rotate, which can change a slow fluid flow to a fast jet.

Nanoscale Impedance Spectroscopy Sensor Technology

Professors Lang, Trumper, and Zahn and master's student Benjamin Cannon are developing a nanoscale impedance spectroscopy sensor technology for nondestructive testing and measurement applications such as an inspection tool in the integrated circuit (IC) industry for applications such as (1) measuring buried semiconductor structures, detecting device states, and monitoring signal flows to verify the IC configuration and operation; (2) detecting mask defects or contamination and mapping the exposed or developed patterns in photoresist, as well as the underlying IC structure, to verify mask alignment; (3) identifying fabrication defects during or after fabrication for the purposes of quality control; and (4) being used to image live circuits by listening to electrical signals in an IC as it functions, thereby verifying the IC configuration and operation.

Photonic Crystals: Enabling Record Efficiency Thermophotovoltaic Solid-State Energy Conversion

Professor John Kassakian, principal research engineer Dr. Thomas Keim, and postdoctoral research associate Dr. Ivan Celanovic have continued their experimental and theoretical investigation of advanced thermophotovoltaic (TPV) spectral control components based on photonic crystal devices Their work on TPV ranges from theoretical investigations and modeling to device fabrication and characterization all the way to system design and implementation. In the past year they have continued to make significant progress on high-temperature photonic crystal and metamaterial-based selective emitters.

Work has continued on a portable 10-W propane-operated TPV power generator. Portable generator continuous operation with GaInAsSb PV diodes and a ceramic burner has been demonstrated with the best efficiencies ever reported.

In addition, a record-breaking selective thermal emitter for the National Aeronautics and Space Administration (NASA) radioisotope TPV system for deep-space probe missions has been demonstrated. This subsystem is currently being tested at the NASA Glenn Research Center.

In summary, this research is continuing to open up new avenues toward record-breaking solid-state heat-to-electricity conversion efficiencies. These findings are being applied toward more efficient solar–thermal and solar–PV energy conversion.

Biomedical Modeling and Stochastic Networks

Professor George Verghese and his research group are focused on (1) biomedical modeling, signal processing, and monitoring (jointly supervised by postdoctoral researcher Dr. Thomas Heldt); (2) structured model reduction; and (3) stochastic networks.

Integrating Data, Models, and Reasoning in Critical Care

Professor George Verghese's group is pursuing one of the core research thrusts of an NIH-sponsored Bioengineering Research Partnership directed by professor Roger Mark of HST. The aim is to develop monitoring approaches and systems that will improve the efficiency, accuracy, and timeliness of clinical decision making in intensive care and perioperative care. The work in this area involves doctoral student Faisal Kashif, master's of engineering student Varun Chirravuri, and UROP student Jerry Wang, all working closely with Dr. Heldt.

A related project, being undertaken in collaboration with Dr. Adre du Plessis of Children's Hospital Boston, and with key involvement by Dr. Heldt and doctoral student Faisal Kashif, studies similar questions for premature babies and neonates in critical care. The focus here is on cerebral hemodynamics, which is especially crucial to development in this patient population. Professor Verghese is spending his 2009 sabbatical year with Dr. du Plessis's group.

Intracranial Pressure and Cerebrovascular Autoregulation

A similar collaboration in the setting of adult patients with conditions such as stroke and traumatic brain injury is under way with Dr. Vera Novak at the Division of Gerontology in Beth Israel Deaconess Medical Center and Dr. Marek Czosnyka of Cambridge University in the UK. Doctoral candidate Faisal Kashif, working with Professor Verghese and Dr. Heldt and supported by a Center for Integration of Medicine and Innovative

Technology Fellowship, has developed a very promising approach to noninvasively measuring intracranial pressure and thereby assessing cerebrovascular autoregulation.

Micropower Medical Technology Platform for Wearable Monitoring

This collaboration between researchers from Texas Instruments and MIT's MTL, involving Professor Verghese's group in LEES (particularly Dr. Heldt and UROP Jerry Wang), is developing a wearable low-power chip platform that enables robust acquisition and processing of a wide variety of biomedical signals indicative of human health.

Stochastic Network Models

Doctoral candidate William Richoux, in research with Professor Verghese, continues to develop and study stochastic network models, representing the collective behavior of stochastic automata at the nodes of a network interacting with the automata at neighboring nodes. Current work is directed at approaches to parameter estimation.

Educational Initiatives

Professors Jim Kirtley, Steven Leeb, and Leslie Norford have developed a first-year project-oriented subject (working title is Physics of Energy) that tries to interest freshmen in energy-related issues. They have done interlocking freshman seminars for the past few years and intend to continue to do so.

Professor Leeb served as a member of the Committee on the Undergraduate Program this year. He also served as the educational outreach coordinator for MIT's Center for Materials Science and Engineering. He participated on the MITEI education task force and assisted in developing the new energy minor approved by the faculty this year. He served as an instructor for MIT's Women's Technology Program summer program, providing a new energy and motor-building activity for 40 visiting high school women and five high school teachers, among other outreach activities.

Professor Zahn has worked with MIT OpenCourseWare (OCW) in greatly improving his three OCW sites for 6.013 Electromagnetics and Applications; 6.641 Electromagnetic Fields, Forces, and Motion; and 6.642 Continuum Electromechanics. These sites include freely downloadable textbooks and solutions manuals as well as videos on electromagnetic fields and energy.

Professor Schindall, as codirector of the Bernard M. Gordon–MIT Engineering Leadership Program, is actively engaged in developing and teaching courses and seminars aimed at developing the character, vision, and skills necessary for future engineering leaders. In connection with this program, and in conjunction with visiting lecturer Blade Kotelly, he has developed and piloted an undergraduate course in engineering innovation and design.

Honors and Awards

Professor Joel Schindall was elevated to the grade of fellow in the Institute for Electrical and Electronic Engineering.

LEES Transfer to Research Laboratory of Electronics

Effective July 1, 2009, LEES will merge into RLE as part of a growing emphasis on energy-related research in RLE. As a result of this merger, RLE will establish a seventh research theme, electromagnetic and energy, which will retain the LEES name and will comprise the work of the newly affiliated former LEES faculty as well as RLE investigators already conducting energy-related research.

Future LEES President's Reports will be incorporated into the RLE report.

Joel Schindall
Bernard Gordon Professor of Electrical Engineering and Computer Science
Acting Director

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