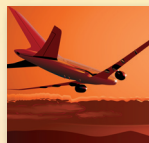




CPES

Center for Power Electronics Systems



INTRODUCING CPES



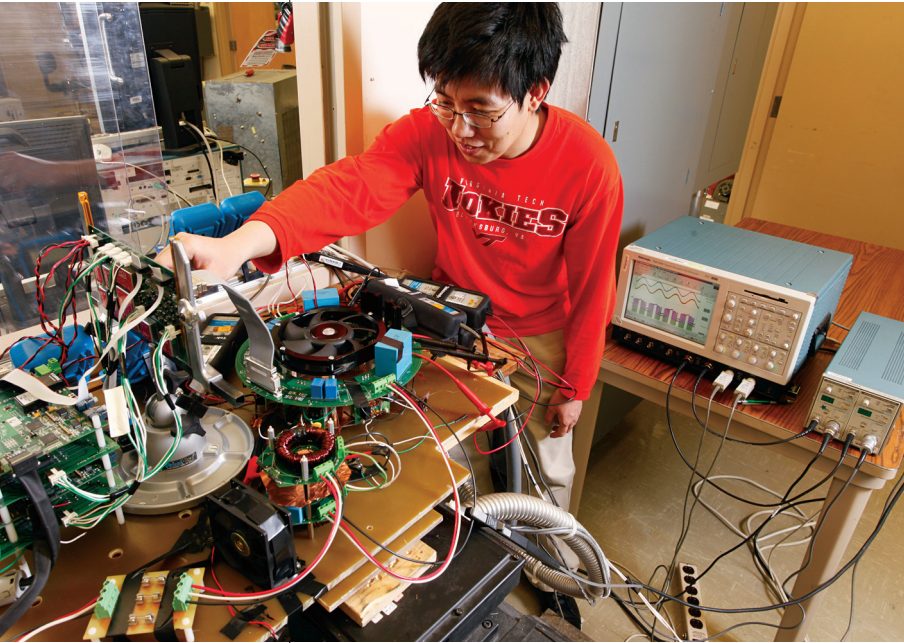
The Center for Power Electronics Systems is a \$4 million/year research center dedicated to improving electrical power processing and distribution that impact systems of all sizes—from battery-operated electronics to vehicles to regional and national electrical distribution systems.

Our mission is to provide leadership through global collaborative research and education for creating electric processing systems of the highest value to society.

CPES has a worldwide reputation for its research advances, work with industry to improve the entire field, and its many talented graduates. From 1998-2008, CPES served as an Engineering Research Center (ERC) for the NSF. A collaboration of five universities and many industrial firms, the CPES ERC was the largest-ever collaboration of power electronics researchers. During the ERC period, CPES developed the IPEM, a standardized off-the-shelf module that has revolutionized power electronics.

Today, we are building on that foundation so that power electronics can fulfill its promise and reduce energy use while helping electronics-based systems grow in capability.

WHAT'S INSIDE



WHAT IS THIS?



The image above is a 2D Code Microsoft Tag. With a camera-enabled mobile phone and Microsoft's Tag Reader app, you can snap a photo of the code and be instantly directed to the corresponding page at www.cpes.vt.edu. Look for our Tags throughout this brochure and discover more of CPES!

Get the free phone app at <http://gettag.mobi>

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ABOUT CPES

Changing the way electricity is used

Electricity is used at an average rate of more than 50 billion kilowatt-hours worldwide every day. With few exceptions, the electricity is not used in its raw form. Instead, the machines, motors and electronics equipment convert electricity into the specific form they need. This conversion of electrical power from one form to another increasingly uses the technology of power electronics. The Center for Power Electronics Systems is working to dramatically improve the efficiency, quality, and uses of power electronics systems.

An enabling infrastructure technology

Power electronics is an “enabling infrastructure technology.” Worldwide sales of power electronics equipment top \$100 billion each year and support another \$1.1 trillion in hardware/software electronics. Advances in power electronics technology can reduce losses in power conversion and more precisely control electrical power for manufacturing operations. These, in turn, can increase energy efficiency of equipment and processes using electrical power, raise industrial productivity and improve product quality. Such advances could have a huge impact on U.S. industrial competitiveness.

Environmental benefits

Power electronics can also yield environmental benefits. For example, the EPRI Electricity Technology Roadmap identified high-efficiency end-uses of electricity as one of the key challenges to achieving its vision of an extremely reliable power delivery system that increases economic growth

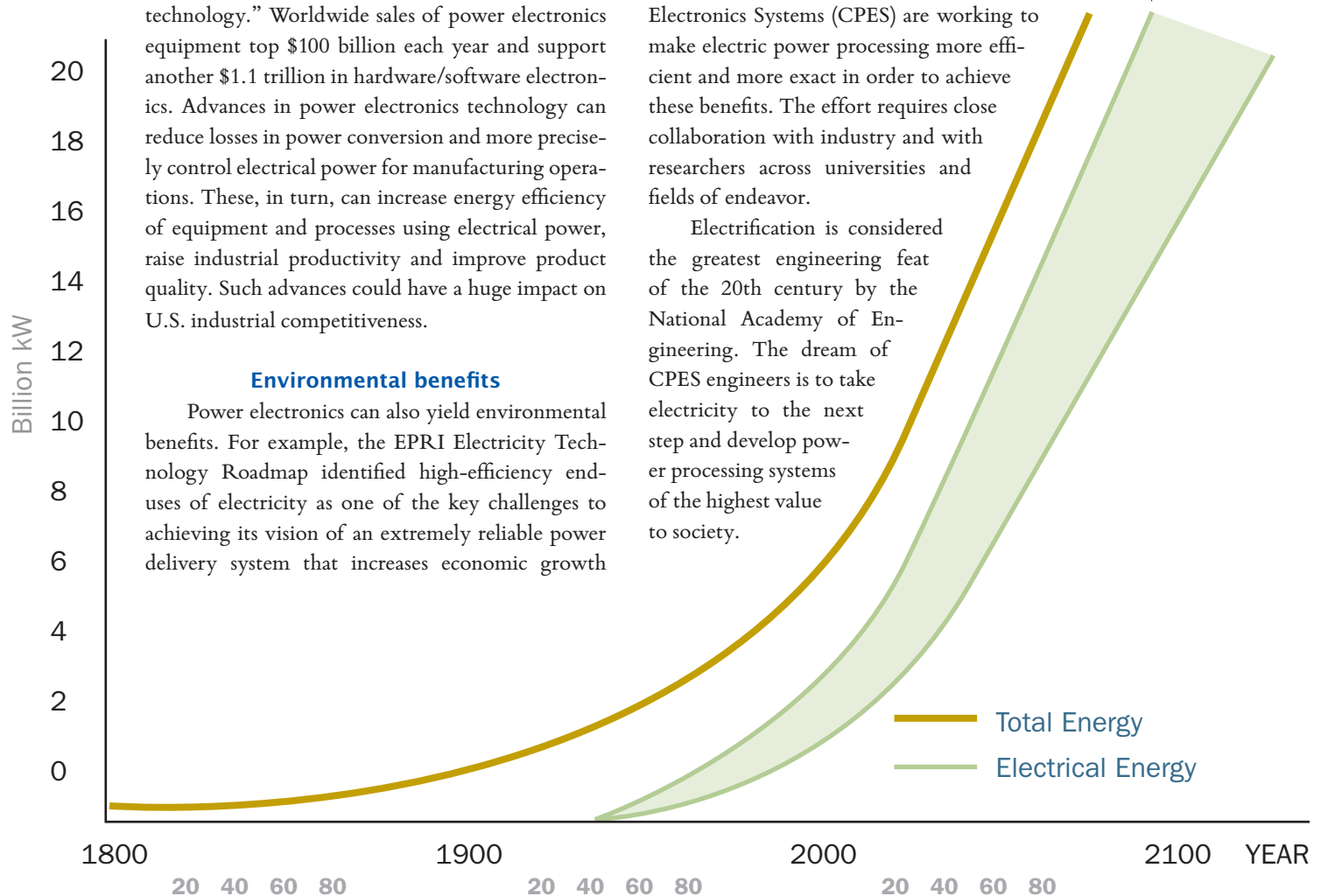
rates with minimal environmental impact. High-efficiency lighting systems, motor drives and power supplies were listed among the highest priority capability gaps. The efficiency of all of those applications can be greatly improved with advanced power electronics.

Reducing energy consumption

With the widespread use of power electronics technology, the United States would be able to cut electrical energy consumption by 33 percent. The energy savings, by today’s measure, is equivalent to the total output of 840 fossil fuel-based generating plants. This would result in enormous economic, environmental, and social benefits.

The engineers of the Center for Power Electronics Systems (CPES) are working to make electric power processing more efficient and more exact in order to achieve these benefits. The effort requires close collaboration with industry and with researchers across universities and fields of endeavor.

Electrification is considered the greatest engineering feat of the 20th century by the National Academy of Engineering. The dream of CPES engineers is to take electricity to the next step and develop power processing systems of the highest value to society.



APPLICATIONS

Power management for information and communication technology

As processor-based systems become more complex, more power is consumed by both active and standby systems. At the same time, more systems are going portable and the emphasis on extending battery life adds more challenges to power management.

Designers are now striving for high efficiency at both full and light loads.

Since the U.S. Environmental Protection Agency (EPA) added computers to ENERGY STAR specifications, many of the major system manufacturers, such as HP, Dell, Cisco, IBM, and Intel are pushing for even higher energy efficiency. Their current near-term target is 92 percent efficiency at 20 percent load, 94 percent at 50 percent load, and 92 percent at full load.

Historically, the goals of efficiency, thermal management, voltage regulation, reliability, power density, and cost drove power electronics design. These factors remain critical, particularly in the face of falling supply

voltages and rising current demands. Yet, as multiple voltages proliferate across the PC board, the challenge becomes distributing and managing power across the board.

It is time to revisit the power architectures that are in general use and have evolved over time. These architectures may no longer be the optimal solution.

DID YOU KNOW?

CPES research is directed to several applications, including power management for IT and communications point-of-load converters for power supplies, vehicular power converter systems, and renewable energy systems.

Although these applications range in size from millimeters to miles, many of the same basic power electronics principles apply.



Power electronics impacts IT applications from handhelds to server farms.

GET THE DETAILS!

Read about power management research at www.cpes.vt.edu/area/PowerManagement



Point-of-load conversion for power supplies

Although they are a subset of power management, point-of-load (POL) conversion for power supplies is becoming a major power electronics application in its own right. POL converters are being used in microprocessors for computers, GPS systems, cell phones, PDAs, and other portable electronics. These applications require higher output current, faster transient response, lower output voltage, and tighter output voltage regulation than conventional technology provides.

POL converters are placed near the processor consuming the power. This system avoids long wiring distances between the converter and processor that is found in conventional power supplies and provides a precise voltage supply that meets low-voltage/high-current needs.

Merely employing POL converters, however, is not enough for tomorrow's applications. Using today's POL technology to meet ever-stringent requirements would mean larger output and decoupling capacitors,

which would raise the cost and occupy too much space on the motherboard.

CPES researchers are seeking alternative POL technology and are investigating different power system architectures, control methods, power conversion, topologies, packaging, more integration, and improved thermal management solutions.

CPES invented the multi-phase voltage regulator module (VRM) based on paralleling multiple buck converter cells in 1997 and today, every computer with an Intel microprocessor uses that CPES technology. In 1997, the biggest application for VRs was microprocessors for computers; today, applications are growing in quantity and variety.

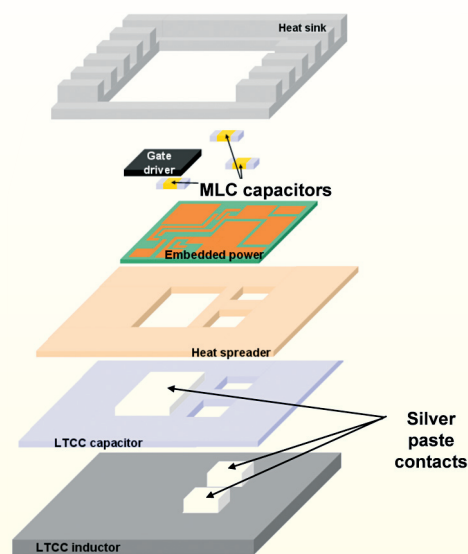
GET THE DETAILS!

Read about POL research at www.cpes.vt.edu/area/POL



POL TECHNOLOGY

The latest Point of Load (POL) technology developed at CPES uses novel packaging called "Stacked Power" that allows for active devices to be embedded inside a ceramic layer of high thermal conductivity. This frees up the top and bottom sides for the integration of other circuit parts. The vertical integration allows for layouts with low circuit parasitics so that efficient high-frequency operation can be realized. The passives are integrated with the active layer by means of Low-Temperature Co-fired Ceramic (LTCC). LTCC technology enables the integration of low-profile inductors with high current capabilities. The 3D integrated system enables the integration of bulky magnetics components in the form of a low profile substrate upon which the active components can be integrated.



Conceptual Structure of CPES 3D Integrated Power Supply

APPLICATIONS

Vehicular power conversion systems



Transportation vehicles are becoming more and more electrical, from electric/hybrid cars, electrified trains, to all-electric ships and more-electric airplanes. Power electronics plays a large role in improving the efficiency of these electricity-based vehicles.

CPES has a long history of research in power-electronics-based vehicular power systems, sponsored by industry partners and agencies like ONR, NASA, AFOSR, DARPA, ARL, DOE, and NSF. The Center's vehicular power system research is focused on three major areas:

1. High-density Power Converters – use advanced devices, passives, circuits, control and packaging to achieve small volume and low weight converters, which are essential to vehicular system applications.

2. Modular Plug-and-Play Power Electronics Building Blocks – develop modular power converters, and corresponding control/communication strategies for multi-functionality, reconfiguration, better performance, lower cost, and higher reliability.

3. System Architecture, Modeling, Analysis, and Control – develop design and evaluation methodology for optimal system architecture; develop multi-level models for characterizing system behaviors from stability, power quality, to EMI; study system control and power management strategy.

GET THE DETAILS!

Read about research in vehicular power conversion systems at www.cpes.vt.edu/area/vehicular



Renewable energy systems

Building upon long-time research experience in space power systems (including solar/photovoltaic sources, battery charger/discharger, and dc distribution), CPES has a strong research program in renewable energy systems.

This research focuses on three major areas:

1. Sources — dedicated converters for interfacing renewable sources (photovoltaic, wind, battery, etc.) to the power distribution system
2. Smart and energy-efficient appliances
3. Innovative power distribution systems and microgrid

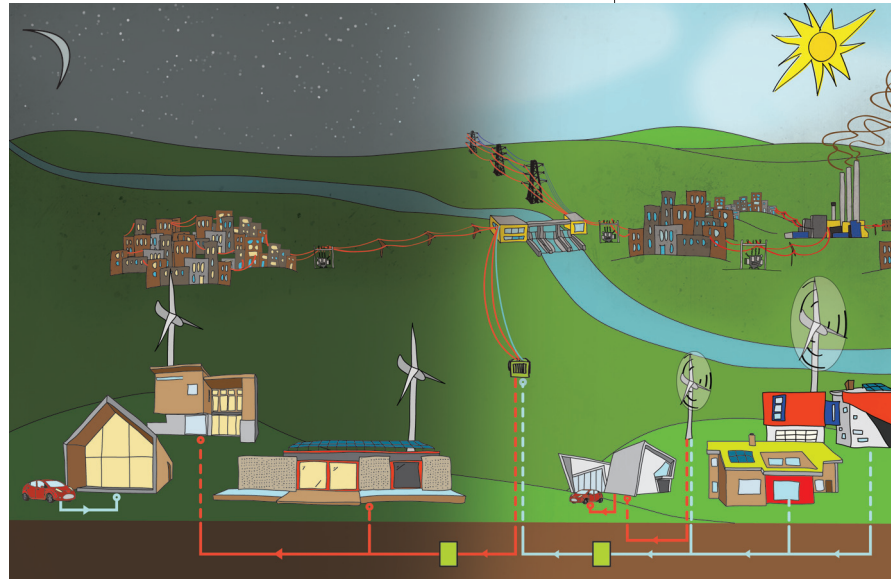
Sustainable Building Initiative

The flagship research project in this area has been the sustainable building initiative (SBI). CPES is developing a dc-based renewable energy system as a testbed for future sustainable home electric power systems.

SBI features include:

- Renewable energy generation (e.g., solar systems, wind)
- Responsive illumination control (e.g., LEDs, CFLs)
- Sensor, monitoring, and control network (wired or wireless) for energy sources, appliance, lighting, and process energy management; wired or wireless
- EV/plug-in hybrid generation/charging/storage
- Process-optimized appliance operation control (air, water, HVAC, ...)
- Local fuel-based energy generation (e.g., micro-CHP systems)
- Ability to continue operating in islanded mode and thus ride through most grid outages
- Bidirectional connection to the grid that allows energy trading

The testbed contains various energy sources, including a 3.5 kW turbine generator, 5 kW PV solar panels, a lithium-ion battery bank for energy storage, and a plug-in hybrid car with bidirectional energy flow. The electrical system has two dc buses: a high-voltage dc bus and a low-voltage dc bus. The high-voltage bus is operated at ~380 V, powering HVAC, simulated



kitchen loads, and other major appliances. The low-voltage bus is chosen to be at 48V to coincide with the standard telecom voltage, powering computer loads and LED lighting. The whole system is connected to the utility grid via a bidirectional dc-ac converter.

Nanogrid

Homes that rely on renewable energy may also function as nanogrids. The interconnection between the home and the electric grid can be designed so that the home can operate both as a connection on the grid and as an island — an independent electrical system, managing internal sources and loads. In the independent case, energy storage becomes a critical component. Nanogrids can be further extended from single house systems to multiple homes, buildings, data centers, and neighborhoods.

Alternative energy systems will add complexity to the electrical power system with the coupled dynamics between thousands of distributed actively-controlled generation, storage, and consumption units. This “complexity curse” could be managed by using a single power-electronics-based load/source interface for each nanogrid.

Each nanogrid could then be dynamically independent of the grid, but dispatchable by the utility operator.



GET THE DETAILS!

Read about recent developments in renewable energy systems at www.cpes.vt.edu/area/REN



TECHNOLOGY

Throughout its history, CPES has developed technology at the forefront of power electronics, from early non-destructive testers to voltage regulators found in every Intel-based computer today. Recently, while serving as an Engineering Research Center for the National Science Foundation (NSF), CPES developed the technology for integrated power electronics modules (IPEMs). IPEMs are standardized off-the-shelf units that are helping to revolutionize how power electronics is used; they replace expensive, custom, low reliability systems.

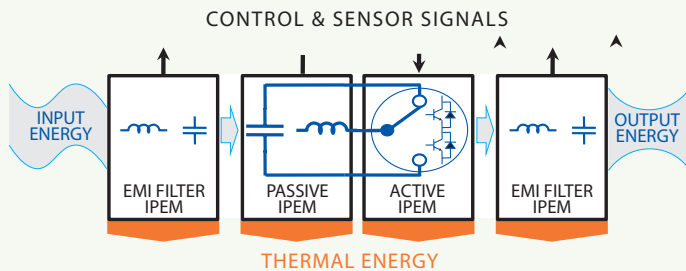
CPES research is now building on that IPEM foundation,

while pursuing additional directions, including power management architectures, modeling, and integration strategies. This work is at the forefront of the field and involves researchers from many disciplines and advances in a variety of areas.

The five general areas of pursuit:

- Power conversion topologies and architectures
- Power electronics components
- Modeling and control
- EMI and power quality
- High-density integration

IPEM Functional Partitions



Basic functions of a power electronics system:

1. Switching elements to regulate energy flow
2. Electromagnetic energy storage and transformation for proper functioning of switching, control, and filtering
3. Spatial and temporal operations control
4. Thermal management
5. Mechanical/structural integration of components, modules, and total assembly

IPEM

In 1998, U.S. power electronics systems were typically custom-designed units containing 300–400 electronics components, with little integration and fairly low reliability. Individually packaged power devices were mounted on a heat sink, with the driver, sensors and protection circuits implemented on a printed circuit board (PCB), which was mounted on top of the power devices. In addition, a control circuitry and microprocessor board was mounted on top of the driver board. The manufacturing process was labor intensive and costly, with a typical cycle time between 16 and 24 months.

CPES was formed as an NSF Engineering Research Center (ERC) to change the paradigm and develop IPEMs — lower-cost,

standardized, off-the-shelf units for any range of power application. CPES drew on the expertise of five universities and scores of industrial partners.

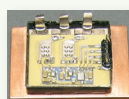
During a 10-year period, CPES developed three standard-cell IPEMs for integration in devices: active IPEMs, passive IPEMs, and filter IPEMs. Industrial adoption was swift. In IT, the IPEM has been adopted to power the new generation of desktop processor.

Before CPES, the concept of an Intelligent Power Module (IPM) was only in its infancy, but now it is widely used in low-power motor drives. The IPEM has also become a mainstream concept in high-power applications.

IPEMS AND THEIR APPLICATIONS



Flip-Chip
on Flex
800 V, 90 A



Embedded
Power
800 V, 80 A



Double-Sided
Cooling
SC-IPEM



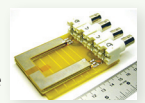
3D Active/
Passive/Thermal
Integration
Stacked Power
24 A, 260 W/in³



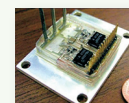
Passive Module
Packaging
LC in DIP



Integrated
EMI filter
Differential and
Common-Mode



Integrated
Transmission
Line EMI Filter
Differential and
Common-Mode



Flex Power
600 V, 15 A
Standard-Cell
IPEM

Power conversion topologies and architectures

Power processing systems have fundamentally transformed in recent years, from centralized power to distributed power.

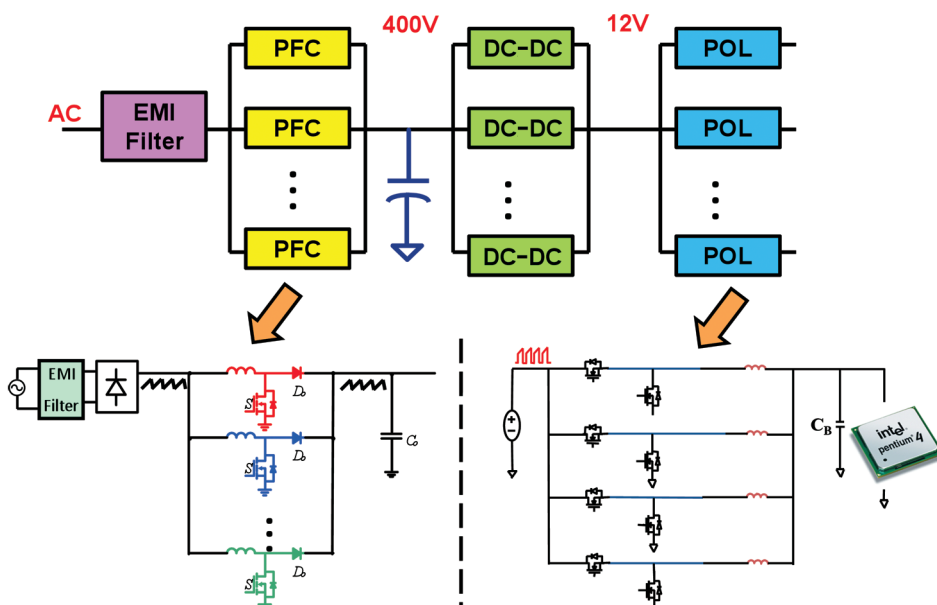
For example, new-generation microprocessors operate at less than 1 V, higher than 100 A, and run at multi-GHz clock rates for maximum speed-power performance. These operating parameters create very fast dynamic loads that demand high current slew rates during transients and have forced a move from the traditional, centralized power supply architecture to a distributed power system (DPS). A dedicated point-of-load converter is placed in each output unit close to the high-speed processor, while the front-end power processing that interfaces with utility lines is performed at a system level.

This kind of DPS approach has not only enhanced

system performance and improved the design and manufacturing process, but also has opened the opportunity to develop a standardized modular approach to power processing.

CPES has been at the forefront of this research, and has developed a number of innovative power conversion technologies based on the modular building block concept. CPES research in this area includes power system architecture, system interface stability and requirements, electromagnetic interference / electromagnetic compatibility at the system level, filter design, single-phase power factor correction circuits, three-phase power factor correction circuits, high-frequency dc-dc PWM converters, as well as resonant converters, and integrated single-phase and three-phase PFC/dc-dc converters.

DISTRIBUTED POWER SYSTEMS



GET THE DETAILS!

Read about research in power conversion topologies & architectures at www.cpes.vt.edu/area/topologies



Power electronics components

Advanced architectures and topologies require superior power electronics components, including power semiconductor devices, magnetic components and capacitors. Developing these components is a major effort in CPES laboratories.

Low profile magnetic components — The design and integration of magnetic components is growing in importance. CPES is studying new high-frequency magnetic materials suitable for high-frequency applications in the multi-MHz range. For accurate characterization and optimal designs, CPES researchers have developed a combination of high-frequency modeling and finite element analysis.

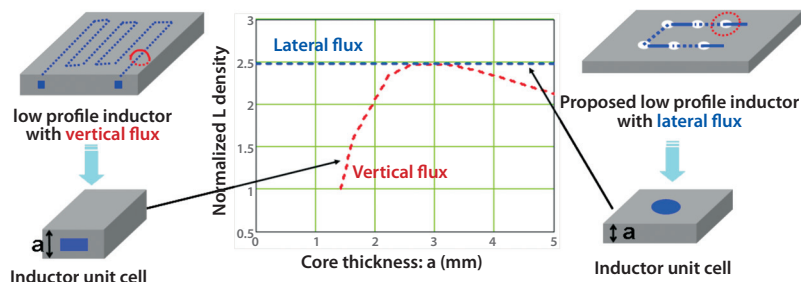
With the increased popularity of portable electronics, low-power dc-dc converters are growing more

popular. However, bulky magnetic components are a major barrier for integrating a dc-dc converter into a single chip. For example, in a conventional embedded winding with vertical flux, the inductance density will suffer when the core thickness is very thin. CPES is exploring 3-D integrated technology, such as using a low-profile inductor with a lateral flux pattern as the substrate. This can provide a large inductance density even with very thin core thickness.

Silicon carbide MOSFETs and JFETs — With the recent developments in wide-bandgap semiconductor devices, silicon carbide (SiC) JFET and power MOSFET have become two candidates for commercialization. Featuring high-blocking voltage, high-workable temperature and low on-state resistance, SiC switches have shown great potential in high-power, high-voltage, high-frequency, and high-density (H4) applications. CPES has been working with device manufacturers to evaluate the performance of these devices, and investigate their use in H4 converters.

Early results for SiC MOSFETs show a blocking capability that is at least two times better than Si MOSFETs with a five-times reduction in on-resistance. SiC MOSFETs also perform well under high temperatures. SiC IGBTs, on the other hand, have exhibited much higher switching speed and lower switching loss compared to similar Si IGBTs.

SiC JFETs also show promise and have been tested both with ultra-fast gate drive circuits and with regular switching speed. In both cases, SiC JFETs achieve much higher power density than convention Si devices.



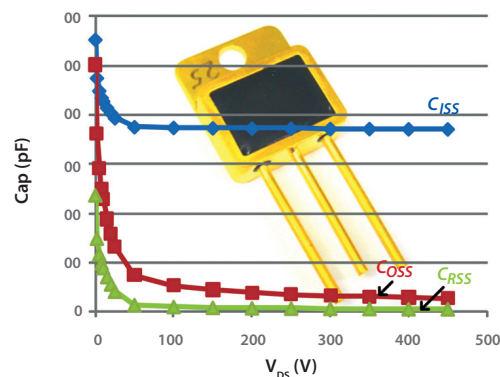
popular. However, bulky magnetic components are a major barrier for integrating a dc-dc converter into a single chip. For example, in a conventional embedded winding with vertical flux, the inductance density will suffer when the core thickness is very thin. CPES is exploring 3-D integrated technology, such as using a low-profile inductor with a lateral flux pattern as the substrate. This can provide a large inductance density even with very thin core thickness.

Test performance surpasses that of commercial surface-mount power inductors of a similar value and outperforms the power handling capability of on-chip inductors designed to operate at similar circuit conditions by a factor greater than ten. To further improve the performance and reduce the size of the inductor, different magnetic structures and flux patterns inside the core, as well as the flux coupling, are being investigated.

Switch structures — CPES has been investigating different switch structures since 1997, such as the

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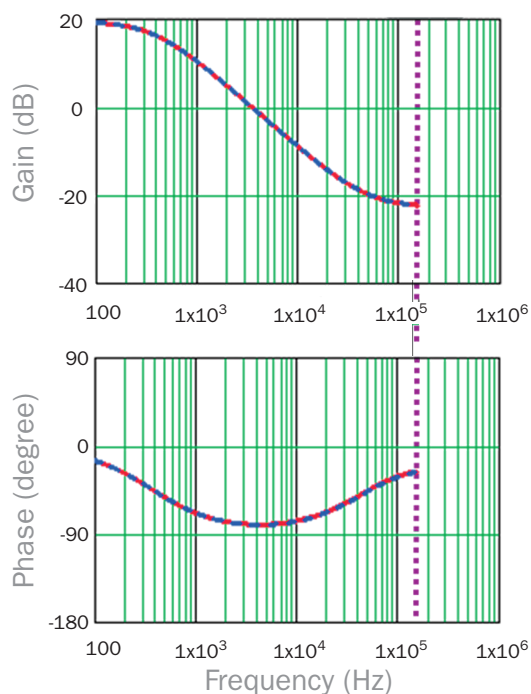
Read about components research at www.cpes.vt.edu/area/components



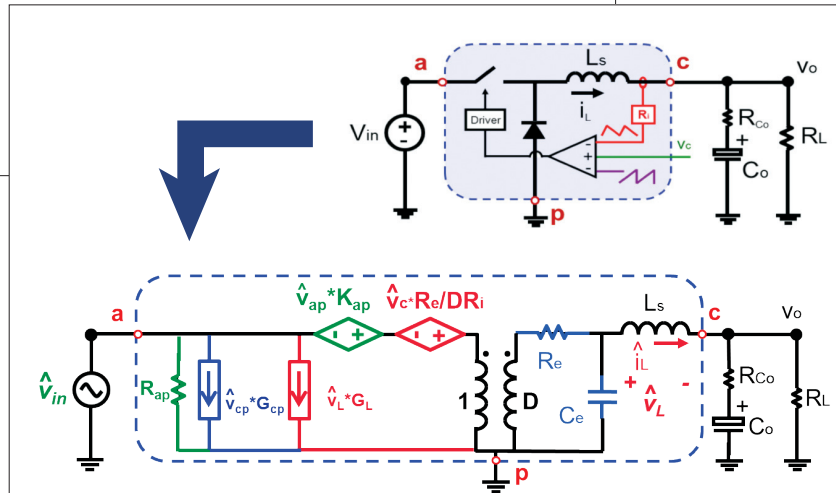
Modeling and control

CPES has historically been at the forefront of power electronics developing advanced modeling and control tools for the design and synthesis of advanced power conversion systems. From its pioneering work in the early 1970's on space and aircraft applications and the back-then nascent telecommunication industry, to the development of power-electronics-only electrical distribution systems for next and future generation data-processing systems and vehicular power systems, CPES has been a true keystone in the power electronics field.

The group has developed a panoply of power conversion models that have unveiled the operation of otherwise complex switching and passive electrical networks, rendering them fully tractable and intelligible for the development of sound time- and frequency-response based control strategies. These models enable the seamless study and analysis of the operation of control strategies and their impact at the device, power converter, and power system levels.



Modeling prediction matches well with Simplis simulation



3-terminal switch model for current mode control

Some key CPES accomplishments in this area are:

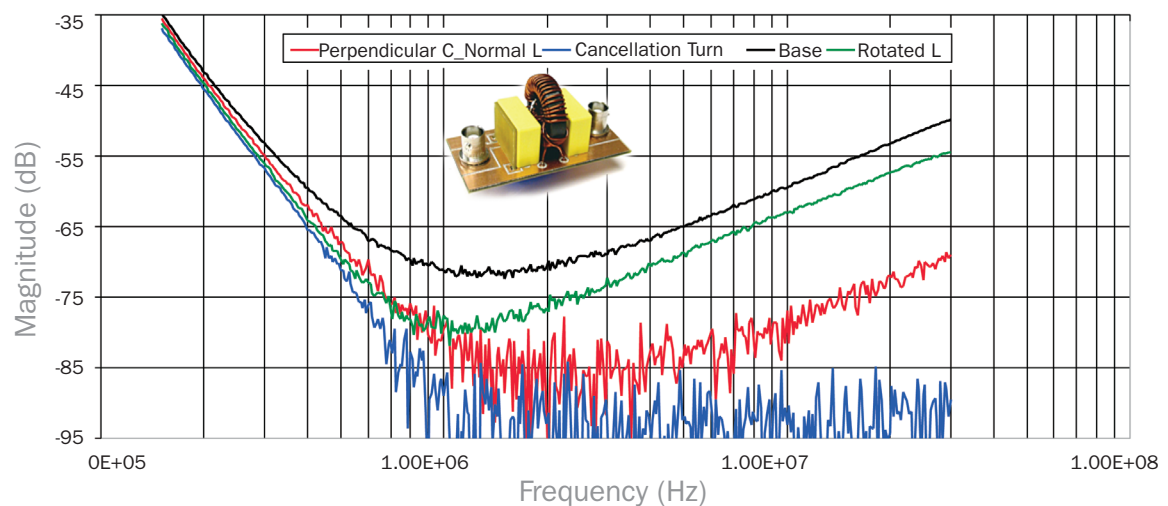
- The PWM-switch model for a variety of current mode controllers.
- Average and small-signal models for dc-dc converters under continuous and discontinuous operating modes, for peak, average and one-cycle current controls, and current- and voltage-mode controls, including paralleled and interleaved dc-dc converters valid for low and frequency ranges beyond half of the switching frequency.
- Synchronous d-q frame average and small-signal models and controls for multi-phase and multi-level ac-dc, dc-ac and ac-ac PWM power converters and synchronous d-q frame average models of multi-phase multi-pulse ac-dc rectifiers.
- Stability theory and prediction of dynamic interactions for dc, hybrid dc-ac, and ac power electronics distribution systems with high penetration of regulated power converters (constant power loads).
- Hierarchical modeling of large power electronics conversion systems for data centers, distributed generation and vehicular power electronics systems for the study of power quality, small- and large-signal stability.
- Terminal-behavior characterization and black-box modeling of power electronics components for the prediction of low frequency dynamic interaction and converter performance and for the prediction of conducted electromagnetic interference (EMI).

GET THE DETAILS!

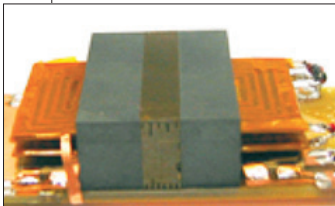
Read about modeling and control at
www.cpes.vt.edu/area/modeling



EMI and power quality



Modern switching-mode power electronics systems generate significant conducted electromagnetic interference (EMI) in a broad spectrum. This EMI can hurt the normal operation of other electronics systems and must be suppressed to an acceptable level before it can propagate. EMI noise is traditionally categorized as either differential mode (DM) or common mode (CM) noise. DM noise is the noise current flowing within the power delivery paths, while CM noise is the noise current flowing between the ground and the power circuits.



Integrated EMI filter. Differential and common mode.

Although EMI is a wide and varied field of study, most of the EMI research at CPES focuses on the generation, mitigation, propagation, measurement of EMI in power electronics systems, as well as the improvement of their power quality.

Recent studies

1. Generation and characterization of EMI noise
2. Parasitic reduction and cancellation for EMI filters
3. EMI noise, separation and measurement techniques
4. High power density hybrid EMI filter design for motor drive system
5. CM noise reduction with balance and parasitic cancellation techniques
6. Active EMI filters
7. Integrated EMI filters with planar structure

GET THE DETAILS!

Read about EMI and power quality at
www.cpes.vt.edu/area/EMI



High-density integration

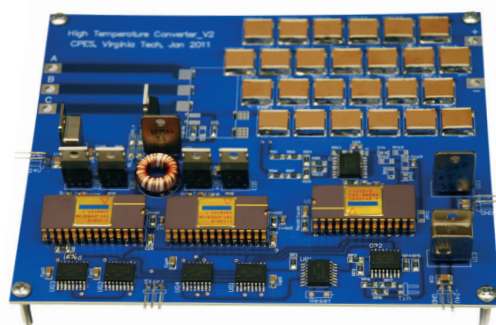
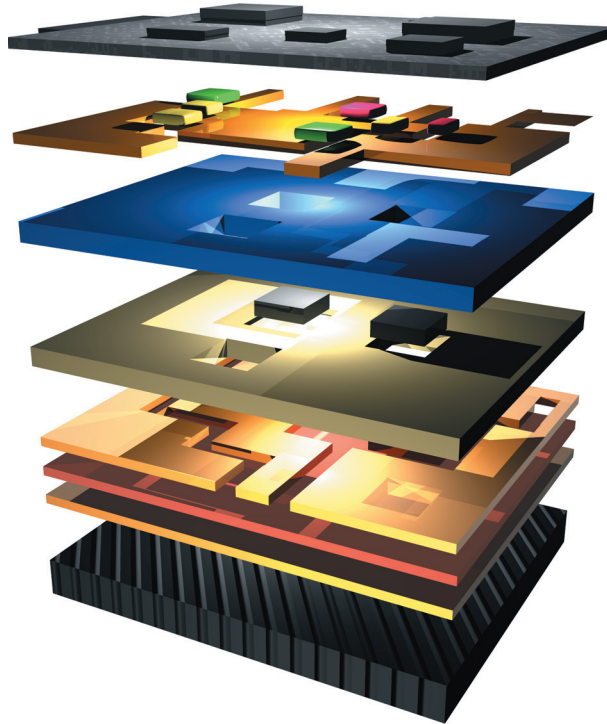
The emergence of wide-bandgap semiconductors, such as silicon carbide (SiC) and gallium nitride (GaN) makes it possible to operate power converters at frequencies beyond 5 MHz and temperatures above 200° C. As the switching frequency increases, switching noise shifts to higher frequencies and can be filtered with small passive components — leading to improved power density.

Higher operating temperatures enable not just increased power density, but also the ability for power electronics-based systems to operate in harsh environments, such as military, transportation, and outdoor industrial, and utility systems.

High-temperature, high-frequency power electronics systems, however, require more than just better semiconductor devices. Designers must also consider materials, gate drives, controller, passive components, packaging, and cooling. The scope of work includes:

- High-temperature integration — Reliable direct-bond-metal substrate; different die-attach technologies for thermo-mechanical reliability; high-temperature encapsulants for power electronics modules.
- Components: Characterization and modeling of wide-bandgap semiconductor devices; high-frequency magnetics and capacitors.
- Module-level integration: High-temperature packaging of power modules, including gate drives, sensors, and protection.
- System-level integration: High-density power supplies on a chip; high-temperature control components and system integration; integrated packaging of LEDs and drivers.

CPES research in this area follows two coupled paths, leveraging the availability of wide-bandgap power semiconductors and high-temperature passive components and ancillary functions. Both switching frequency and maximum component temperatures are being pushed as high as component technologies, thermal management, and reliability permit.



Above: High temperature 3-phase rectifier using SiC and Si-on-Insulator components.

GET THE DETAILS!

Read about high-density integration at
www.cpes.vt.edu/area/HDI



INDUSTRY CONSORTIUM

CPES faculty, staff, and students are driven by a desire to improve power electronics technology and its use in commercial systems. Improved power electronics will reduce energy use and enable more people around the world to enjoy the benefits that electronics technology can provide.

This CPES goal can only be achieved through very close interaction with industry and commercial firms. Throughout its history, CPES has had close industrial relations and we continue to be one of the strongest university-industry research groups in the field. In support of

this strong relationship, the NSF cited CPES as a model for all Engineering Research Centers for its industrial collaboration and technology transfer.

The heart of this relationship is the CPES Industry Consortium, a group of about 100 firms that support CPES research and students, while helping to formulate and guide research directions that will help all participants in the field. The Consortium offers its members the best mechanism to keep abreast of developments in power electronics and an ideal forum for networking with leading-edge companies and top-notch researchers.

Membership structure

The consortium's multi-tiered structure is designed to meet the varying needs of the power electronics industry.

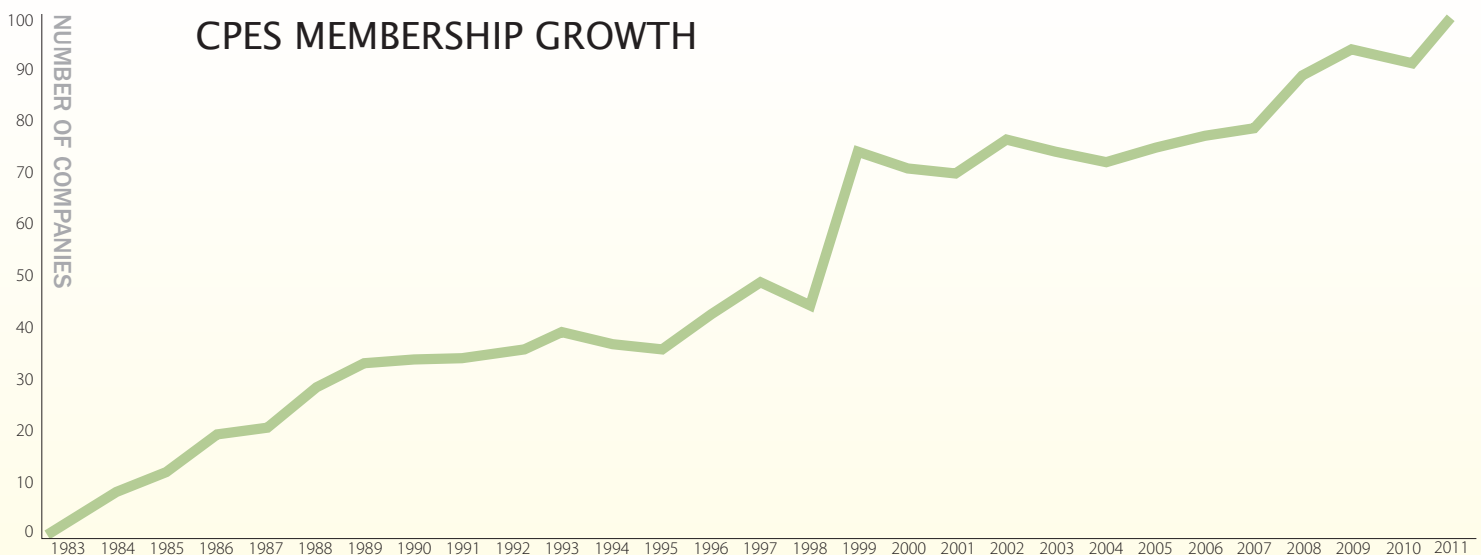
Principal Plus Members (annual contribution – \$50,000) gain tangible benefits via research collaboration with CPES as a member of one of the mini-consortiums on focused research — PMC (Power Management Consortium), HDI (High Density Integration), or REN (Renewable Energy and Nanogrids). They also have easy access to cutting-edge IPs via CPES IPPF (Intellectual Property Protection Fund).

Principal Members (annual contribution – \$25,000) are well positioned to influence and guide CPES as In-

dustry Advisory Board (IAB) members. They also have cutting-edge IP advantage via automatic IPPF (Intellectual Property Protection Fund).

Associate Members (annual contribution – \$10,000) gain the competitive edge, not only through easy access to CPES research results, researchers, and state-of-the-art facilities, but also opportunities for technical exchanges and continuing education to stay updated on new technologies.

Affiliate Members make in-kind hardware/software donations to CPES equivalent to \$10,000 per year. Their contributions must be relevant to CPES research. Membership participation at this level requires Center Director approval.



Membership benefits

Benefits for All Industry Members

- Access to the Center's state-of-the-art facilities, faculty, and student researchers
- Special discount to attend CPES-VT short courses
- Option to send engineers to work with CPES researchers on campus via the Industry Residence Program – a valuable opportunity to cultivate relationship with CPES researchers through daily interactions and gain direct access to the Center's facilities and knowledge base.

Additional benefits for Associate, Principal and Principal Plus members

- Password access to CPES website for publications, presentations, and student directory
- Invitation to participate in the CPES industry webinar series
- Representation on the CPES Industry Advisory Board (IAB) to guide the Center's research direction (guar-

anteed seat for Principal-grade members; representation by special election only for Associate members)

Enhanced benefits for Principal and Principal Plus members

Early and easy access to CPES intellectual properties via automatic CPES IPPF (Intellectual Property Protection Fund)

Tangible benefits for Principal Plus members

Opportunity to leverage funding with other Principal Plus Members and work synergistically with CPES researchers in one of the CPES mini-consortiums on focused research:

- Power Management Consortium (PMC)
- High Density Integration (HDI)
- Renewable Energy and Nanogrids (REN)



CPES allows the opportunity to influence the direction and content of power electronics research. This attracts people who wouldn't normally collaborate with each other. —Ken Phillips

GET THE DETAILS!

Read about industry membership at
www.cpes.vt.edu/public/collaboration



INDUSTRY CONSORTIUM

Mini-consortiums

The CPES mini-consortium model provides a unique mechanism for all participants in power electronics – including industry competitors – to pool efforts to address their common challenges and develop pre-competitive advances.

Companies and organizations join CPES as a Principal Plus Member and choose the mini-consortium option. Annual membership fees are \$50,000. Research results generated within a mini-consortium are shared among its members, and intellectual properties developed under the CPES industry consortium are shared among all Principal-level members as described on the next page.

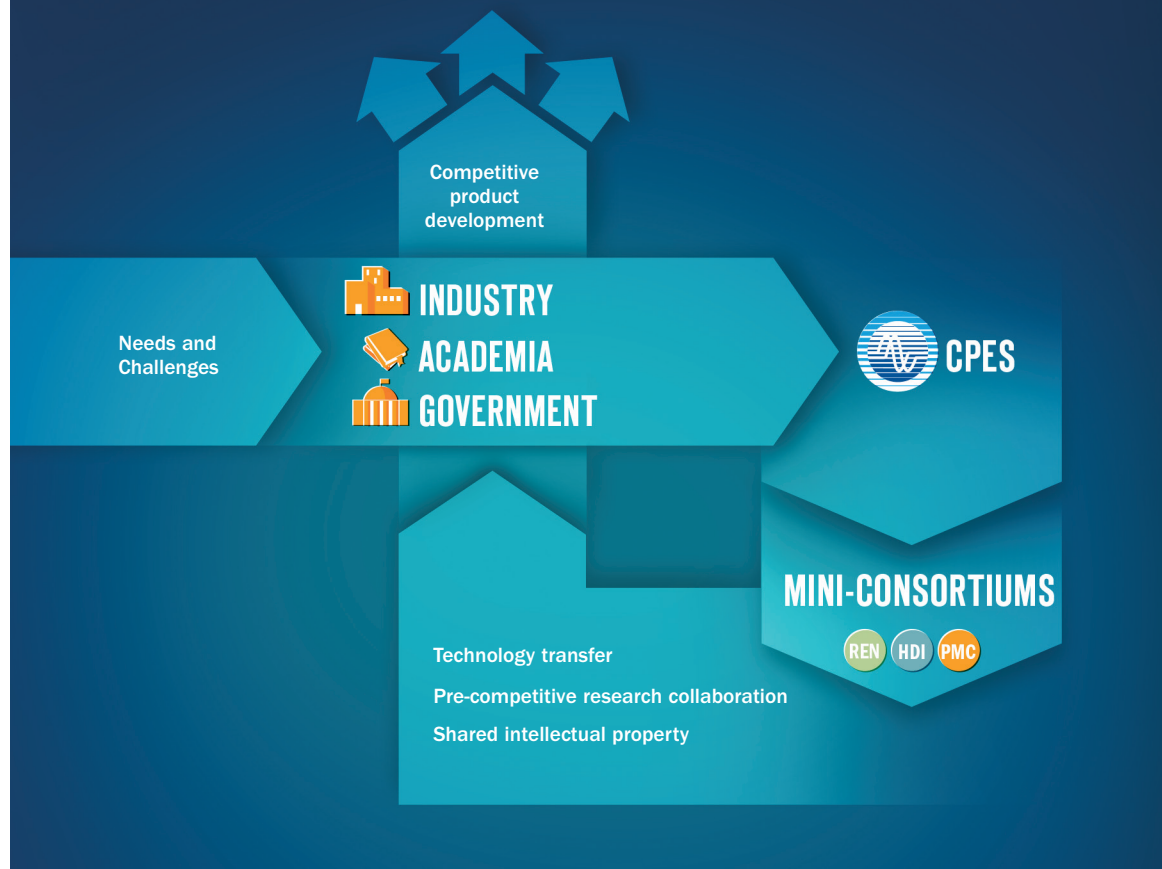
The research and IP benefits are only part of what makes the mini-consortium effective. The distinctive feature of the model is discussion among all participants, which then shapes and guides research toward overcoming the major barriers in the field. Competitive plans and technologies are protected, yet participants can discuss their mutual technical problems. Mini-consortium interactions take place in the quarterly review meetings.

GET THE DETAILS!

Read more about current
Mini-consortiums at
www.cpes.vt.edu/public/miniconsortium



HOW THE MINI-CONSORTIUM MODEL WORKS



Novel IP process benefits all

The CPES intellectual property (IP) process offers unprecedented IP access to all Principal-level members at no extra cost. The CPES IPPF (IP Protection Fund) leverages funding from industry partners to expedite university technology into commercialization.

Principal-level members are invited to join quarterly IPPF telecon discussions with CPES inventors to decide jointly which technologies to protect, with patenting costs covered by IPPF. Once a technology is protected, all Principal-level members are granted a royalty-free, non-exclusive, non-transferable license to use technologies disclosed during their membership years. Engineers can use the technology without involving corporate lawyers and without having to develop their own proprietary technology.

This IP model has been very successful and was instrumental

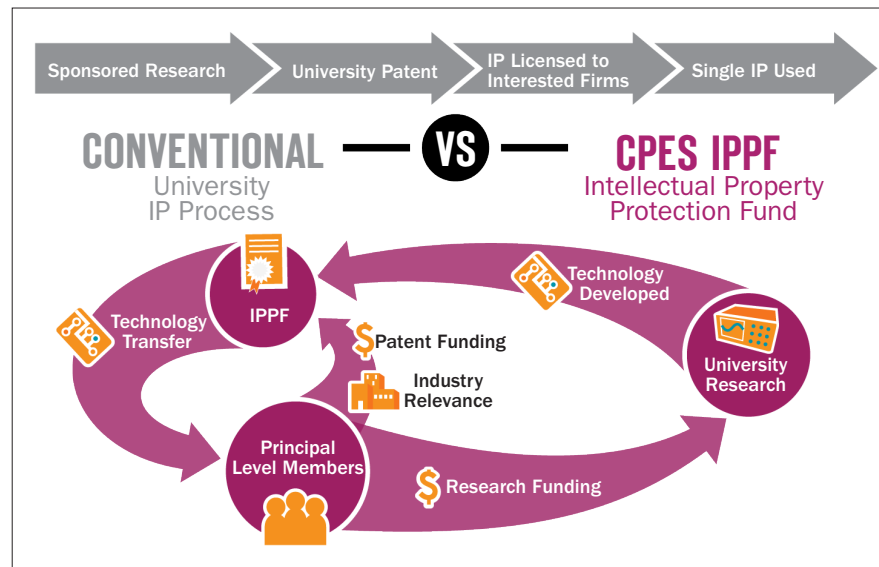
in the success that triggered the U.S. National Science Foundation (NSF) to cite CPES as a model Engineering Research Center for technology transfer and industry outreach.

Pre-competitive technology

Pre-competitive collaboration is encouraged as a successful model in fast-moving fields, such as biotechnology and medicine, where advances in fundamental knowledge are tapped by different firms who then develop their own competing pharmaceuticals or technology. Society can also benefit from pre-competitive collaboration in power electronics, as the technology can move forward much quicker, generating energy efficiency in almost every industry.



CPES has earned more than 81 patents since its inception and its technology is helping systems around the world process electricity more efficiently and more affordably.



“The CPES PMC program provides a very unique platform: while participants focus on the new technologies related to their own business strategy; they get a chance to see something out there that could possibly be the future.”

– Jinghai Zhou, Senior Manager, Technical Marketing & Applications, Monolithic Power Systems

GET THE DETAILS!

Read more about the IPPF at
www.cpes.vt.edu/groups/IP



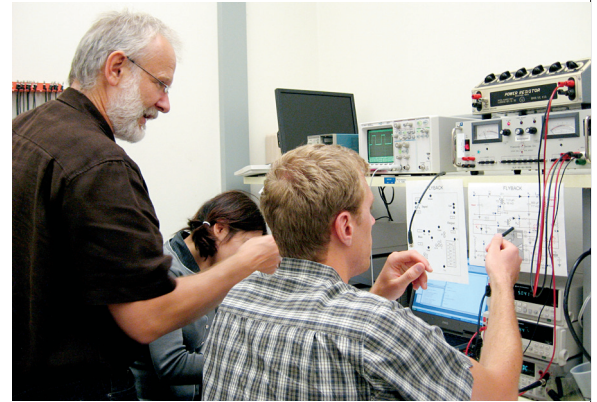
EDUCATION

Short courses for industry

CPES is dedicated to helping engineers and scientists keep their power electronics skills sharp. The Center has been very active in providing on-site and off-site short courses to working engineers.

Previous short courses

EMI
Modeling and Control Design of DC/DC Converters
DC/DC Converters and Voltage Regulators Modules
Analysis and Design of Power Factor Correction Circuits
Advanced Soft-Switching Converter Topologies and Design



Comments from Control Design short course participants

"The hands-on lab that followed each lecture was a great strengthening tool for me. It gave me an opportunity to design and work with the dc-dc converters. Also, it provided an opportunity to ask questions about the material and how it relates."

"I feel the course was an excellent source of information. Both instructors (Fred Lee and Dushan Boroyevich) were very knowledgeable in the modeling and control of dc-dc converters as well as other topics that had risen throughout the course. It also brought other companies together to discuss new technology that may be helpful."

Undergraduate education

In 2002, CPES established a Power Electronics Option for undergraduates majoring in electrical engineering at Virginia Tech. The option can be accommodated within the technical elective requirements for a B.S.E.E. degree. Courses for the option range from controls, circuit design, and microelectronics to power electronics and alternate energy systems. The option was also designed to provide course credit for students working in power electronics on team projects. Participants have shown a keen interest in pursuing employment as well as advanced studies in the field.

Required Courses 6 credits

ECE 4224
Power Electronics

ECE 4205
Electronic Circuit
Design

Technical Electives 9 credits

ECE 4284: Power Electronics Lab
ECE 4206: Electronic Circuit Design
ECE 4214: Semiconductor Device Fundamentals
ECE 4234: Semiconductor Processing
ECE 4324: Electronic Control of Machines
ECE 4334: Power System Analysis and Control
ECE 4364: Alternate Energy Systems
ECE 4405: Control Systems (Fall)
ECE 4406: Control Systems (Spring)
ECE 4964: Field Study
MSE 4984: Principles of Electronic Packaging

Free Electives

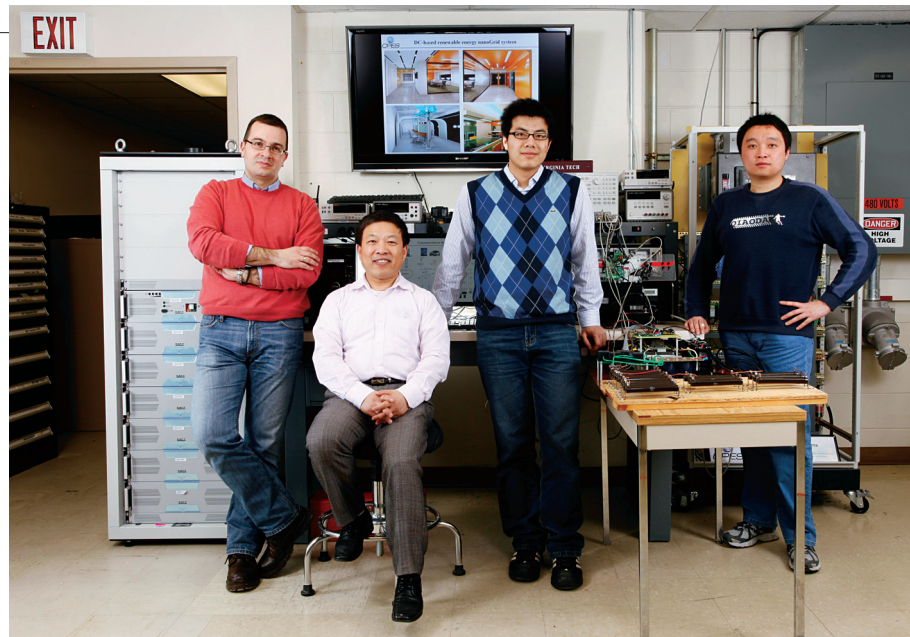
ECE 3964: Field Study
ME 4304: Design in Power Engineering
ECE 4994: Undergraduate Research

Power electronics option at Virginia Tech

Graduate education

CPES graduate students are among the most sought-after in power electronics. Sometimes called, “IP with a brain,” CPES master’s and Ph.D. graduates serve in technical and managerial leadership positions throughout the industry.

CPES is committed to providing these future leaders with opportunities to grow in communications and leadership skills and encourages all graduate students to participate in the Student Leadership Council (SLC). The SLC provides direct student input to CPES management. The SLC also helps coordinate the CPES Annual Conference. A student committee organized the conference and is responsible for the technical program, poster session, general logistics, a conference brochure, proceedings, and proceedings CD.



Courses offered

ECE 5274: Modeling and Control of Three-Phase PWM Converters

Power conversion principles for three-phase pulse-width modulation techniques, control, and converters. Development of averaged models of three-phase rectifiers and inverters in stationary and rotating coordinates. Small-signal models in rotating coordinates and control design. Introduction of switching state vectors and different modulation schemes. Three-phase inverter and rectifier applications. Parallel and multi-level three-phase converters.

ECE 5254: Power Converter Modeling and Control

Nonlinear modeling of power conversion circuit using discrete and average techniques analysis and design of voltage mode and current mode control; parallel module operation and system interactions; distributed power systems; time domain simulation and frequency domain measurement techniques.

ECE 5244: Advanced Power Conversion Techniques

High-frequency resonant, quasi-resonant, and multi-resonant power conversion techniques; zero-voltage and zero-current switching techniques in pulse-width modulation converters and inverters. Pulse-width modulation and frequency modulation; non-linear analysis techniques for resonant and soft-switching converters and inverters. Power factor correction rectifiers and distributed power systems.

continued on next page

EDUCATION

Courses offered

...continued from page 19

ECE 5234: EMI and Noise Reduction Techniques

Theory and practice of E.M. noise coupling; Techniques for noise reduction: shielding, grounding and filtering. Measurement of EMI to comply with government regulation. EMI problems and solutions to switching power supply applications. Design of EMI filter.

ECE 5235: Principles of Electronic Packaging

Design issues, such as electrical, electromagnetic, thermal, mechanical, and thermomechanical, are covered at the lower levels of packaging hierarchy. Materials and process selection guidelines are discussed for the manufacturing and reliability of chip carriers, multichip and hybrid modules. Theoretical bases for design methodology and package reliability. Solid modeling for electrical and thermal designs from chip to board.

ECE 5204: Power Semiconductor Devices

Characteristics, fabrication and application of power semiconductor devices which includes BJT, FET, power diodes, insulated gate and static induction transistors. Device drive requirements and power circuit interaction.

ECE 4284: Power Electronics Laboratory

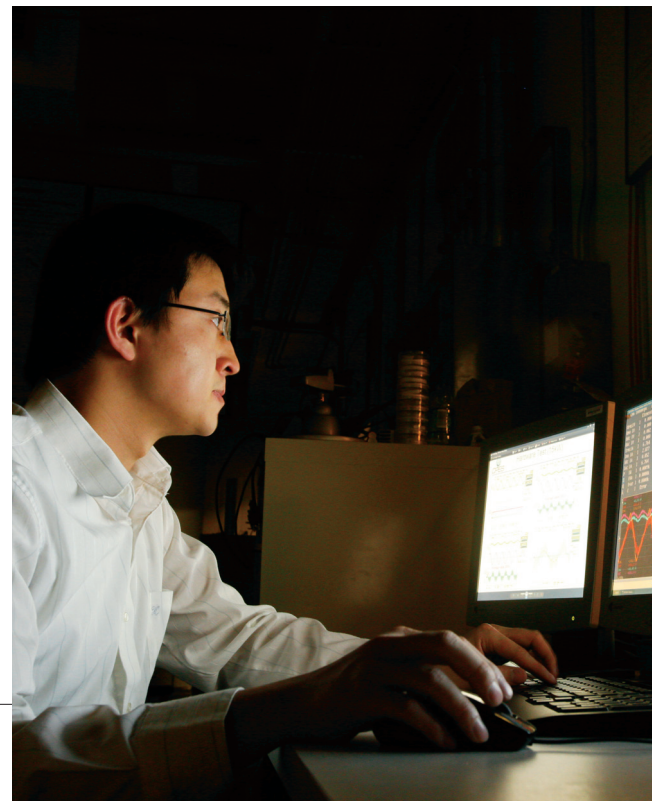
Design and testing of electronic power processing systems for commercial and aerospace applications.

ECE 4224: Power Electronics

Power devices and switching circuits including inverters and converters; electronic power processing and control as applied to industrial drives, transportation systems, computers, and spacecraft systems.

ECE 4205 & 4206: Electronic Circuit Design

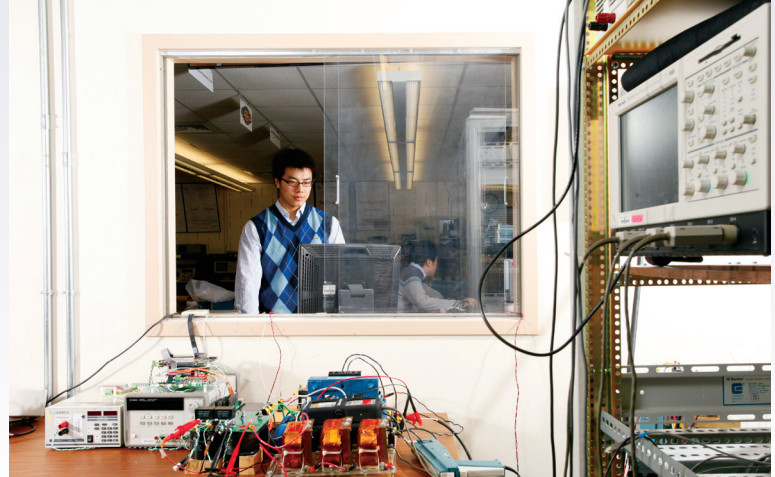
Stability and response of feedback amplifier, wideband amplifier, operational amplifier characteristics, waveform generators and wave shaping, nonlinear circuit applications, signal generators, and photolithography. Design of analog electronic circuits, circuit simulation, response characterization, and printed circuit construction.



FACILITIES

CPES occupies office and lab facilities encompassing more than 19,000 square feet in Whittemore Hall. Research space includes an electrical research lab, an integrated packaging lab, and a computer lab. A research library and a large conference room with voice and video conferencing capabilities support remote site course instruction as well as interaction among CPES collaborators.

The Electrical Research Laboratory has state-of-the-art power testing equipment, dynamometers, prototype PWB manufacturing equipment, an EMI chamber, a clean room, a mechanical shop, and numerous high-end computer workstations.



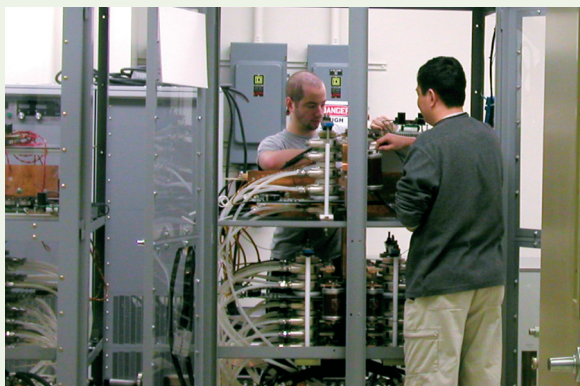
The Power Electronics Research Lab

is equipped with state-of-the-art tools and instrumentation necessary for development of power electronic circuits and systems of all sizes from sub-volts, sub-watts to 6 kV, 1 MW. Standard instrumentation is comprised of GHz oscilloscopes; function generators; network, spectrum, impedance, logic and power analyzers; thermal sensors; and ac-dc bench supplies of all sizes. Specialized equipment includes: thermal test equipment; Hi-Pot tester; 3-D magnetic field scanner; EMI/EMC analyzer; large and small dynamometers; automatic circuit board routing equipment; programmable and variable loads; and liquid cooled heat-exchanger.

The Computer Lab supports all major software used in power electronics analysis and design, including: SPICE, Saber, PSCAD/EMTDC, I-DEAS, Analogy Design Tools Workbench, Ansoft-Maxwell 2-D and 3-D finite-element analyzers, Mentor Graphics and Cadence circuit simulation software, SIMPLIS, TMA, FLOTHERM circuit thermal analyzer software, Silvaco device simulation software, iSIGHT, and Ansys.



FACILITIES



High Power Lab — high power, high voltage power conversion technologies are attracting increasing attention in academia and industry in response to a need for more emerging power electronics applications, including alternative energy and power conversion such as wind power generations, fuel cells, hybrid electric vehicles, and all-electric ships. Enabled by a 2002 award of \$839,337 from the Defense University Research Instrumentation Program (DURIP) paired with CPES cost sharing of more than \$250K for renovations, the electrical research lab has been renovated to accom-

modate medium voltage, megawatts power capability. The facility has two medium voltage 1 MVA reconfigurable transformers, corresponding reactors, capacitors, switchgears, and controllers. A 1 MW Innovation Series medium voltage IGBT drive donated by GE is installed as a programmable load. The complete set-up is capable of testing power converters in various active and reactive operation modes continuously at 1 MVA, 4160 V level. The unique installation distinguishes Virginia Tech as one of a few select universities in the nation with this capability.



Living Lab — CPES has designed and is currently creating a “living lab” with a conference room, library, kitchen, and laundry room. Electricity in these rooms is supplied by a dc bus distribution system with automated source and load management. Local solar panels and a wind power generator are interconnected with battery subsystems and the power company’s electrical grid. When locally produced renewable energy is sufficient, the “living lab” supplies its excess of renewably-generated energy to the electrical grid. Conversely, it draws power from the grid when local energy demands exceed locally-produced renewable energy.

The “living lab” has variety of forward-looking electrical loads, including plug-in hybrid electric vehicles, high-efficiency LED lamps, and energy-efficient home appliances and electronics. These include a washer, dryer, microwave oven, electric range, dish washer, refrigerator, air conditioner, and even home robotics. Home automation technology manages power generation, conversion, and usage through the use of wireless control and monitoring of power consumption.



Conference area with smart wall and kitchen area will be part of the CPES Living Lab. Concepts developed by a+d at Virginia Tech.



The Integrated Packaging Lab

is the first major university facility in the nation devoted to power electronics packaging research. It has the capability to produce FR4, DBC, and thick film hybrid substrates, mount bare die and SMT components, and perform thin film deposition, metal plating, ceramic laser machining, and device wire bonding. Component and module level thermal measurement, environmental and electrical testing capabilities, including device die probing and inspection via microscope, are also available.

HISTORY

ABOUT CPES

PERG

In 1977 Virginia Tech hired Fred C. Lee as an assistant professor to build a power electronics program. Lee had served for three years as a Member of the Technical Staff of the Control and Power Processing Department at TRW Systems.

In its inaugural project, the newly formed Power Electronics Research Group (PERG) built a permanent magnet machine for an electric vehicle with a first-generation giant bi-polar transistor from Westinghouse. PERG also worked with Kollmorgen-Inland Motor to develop

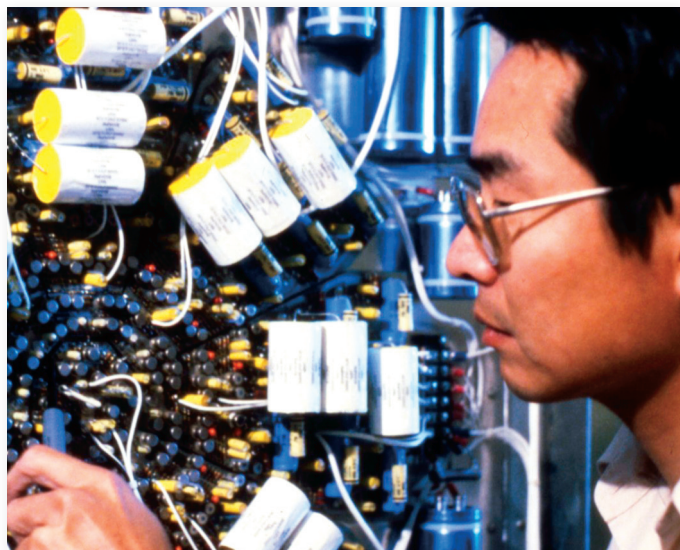
a drive train for the project, which was funded by NASA and supported by the Department of Energy.

During this early period, PERG was also awarded a project funded by Naval Ocean Systems Center in San Diego. The project's objective was to build a solid-state amplifier for very-low frequency transmitters to be used in submarine communications. This research led to the initial development of the phase-shift, full-bridge dc-dc converter, which is used in all computers and telecommunications equipment today.

Soft-switching — A significant breakthrough research effort in the 1980s concerned soft-switching techniques. Virginia Power Electronics Center (VPEC) developed a zero-voltage, zero-current switching, quasi-resonant converter; a zero-voltage switching, multi-resonant converter; and a soft-switching, zero-voltage, zero-current PWM converter. These techniques eliminated virtually all switching losses and switching stresses together with significantly reduced switching noise and EMI.

Board-mounted power — In 1984, VPEC developed a new generation of switchmode quasi-resonant power supplies. These converters, capable of switching at 5–10 MHz compared with 30–40 kHz used commercially, reduced the size and weight of the power supply. The size reduction was significant enough that the power supply could be mounted directly on a digital logic board, where it could provide more precise power regulation. This was a requirement for the next generation of computers. Research on quasi-resonant and multi-resonant and soft-switching PWM power converter technologies resulted in 20 U.S. patents in the years after 1984.

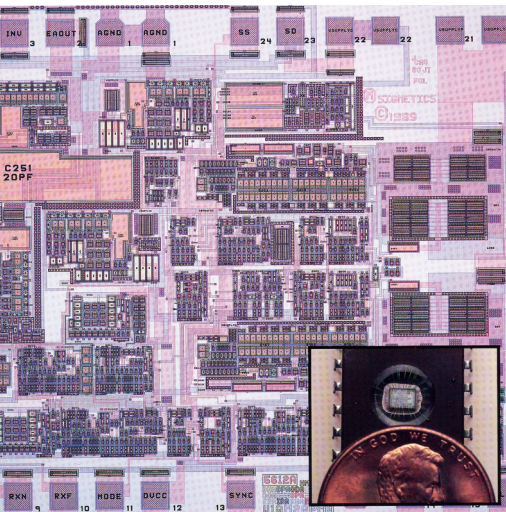
Distributed power — From 1984 to 1991, VPEC worked with IBM-Poughkeepsie to develop high-density, modular power supplies for the future generation of IBM 390 mainframe computers. The objective was to develop a power supply using a stacked power supply system concept and involved converting an ac line into a 360 V dc bus. IBM introduced its new mainframe computer, Model S390, in 1991.



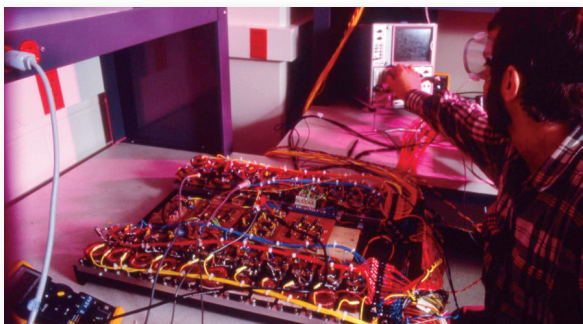
Fred Lee with nondestructive second breakdown tester for power semiconductor devices

Non-destructive characterization — The major cause of failure of many high-power devices — those that were expected to spur the next generation of power electronics technologies — was reverse bias second breakdown. PERG began tackling the issue in 1981 and designed and fabricated a 1000 V, 120 A, nondestructive, second-breakdown tester — the first of its kind in the world. The project was sponsored by the NASA/DOE Electric Vehicle Program and later on by David Taylor Naval Ship Development and Research Center (NSDRC).

Space power — Research on space power systems began in 1977 and escalated in 1985. Two projects of note were the development of a high voltage distributed power system for the Space Station Freedom and the development of a testbed for a power system for the Earth Observing System with NASA-Goddard. Both projects involved extensive modeling, hardware



VPEC developed this high-frequency resonant control chip for a multi-resonant converter in collaboration with Philips-Signetics. The chip is packaged to be mounted on any circuit board.



A researcher adjusts a bi-directional converter developed for use with the NASA space power testbed. The device is pictured above.

design, and testing to ensure the power systems would work perfectly in space.

VPEC established a Space Power Laboratory in 1990 to accommodate its growing space power research program.

In 1991, the NASA Goddard Space Flight Center funded VPEC's construction of a hardware testbed for the space platform power processing system. The testbed system included a solar array simulator, solar array switching unit, battery simulator, battery charger/discharger, and mode controller. This testbed was built and shipped to NASA-Goddard, where it was used to evaluate the NASA Earth Observing System (EOS) power system.

Packaging — In 1986, VPEC received funding from Digital Equipment Corporation to research and develop several high-density dc-dc converter modules using hybrid packaging concepts. This research effort continues today. The CPES Packaging Laboratory was established in 1997.

Thick film — In 1988, General Motors Research Lab and Texas Instruments sponsored a project to develop a thick-film inductor and transformer. VPEC began studying thick-film hybrid techniques and applying them towards design and fabrication of high-frequency multi-megahertz magnetic components. These techniques made it possible for screen printing to deposit both conductive and magnetic materials to form a thick-film inductor and transformer structure for magnetic components. The hybrid transformer was also suitable for other automated productions.

EMI research — In 1989, VPEC introduced a graduate level course on EMI and established its EMI Laboratory in an RF-protected room. One major source of EMI was due to the high rate of change of current and voltage as a result of high frequency hard switching. VPEC developed several key soft-switching technologies, such as zero-current and zero-voltage quasi-resonant, multi-resonant and PWM circuits. These technologies enable power supplies to operate at very high frequencies with

VPEC

In 1983, PERG was formally established as the Virginia Power Electronics Center (VPEC), directed by Fred Lee. In the same year, VPEC formed its Industry Partnership Program and held the first VPEC Annual Seminar. In 1987, VPEC was named a Technology Development Center and received 10 years of funding from Virginia's Center for Innovative Technology (CIT). Over the 10-year cycle, CIT provided a total of \$3 million. By that same year, VPEC's industrial consortium had grown to include 30 member companies.

a controlled rate change of current and voltage. They significantly reduced EMI, and a remarkable greater-than-98-percent efficiency was achieved.

CAD tools — By 1992, the industry had enough computing power to develop effective computing models for power electronics equipment. VPEC developed several successful power electronics modelling software packages. One design package, CADO, used nonlinear design optimization techniques to select converter power stage components at highly detailed levels. A time-domain simulations program, COSMIR, was designed for fast and efficient analysis of switching power converters.

Electric vehicles — Concern for the environment revived during the 1990s and with it, interest in electric vehicles. Another significant VPEC research effort centered around the PNGV project. The goal of this research, sponsored by General Motor, Chrysler, Ford, and the US Army TACOM, was to build and evaluate an electric drive system for electric vehicles.

High power — In 1991, research in power factor correction grew in importance. VPEC started research on several sponsored projects covering power levels from less than 100 W to higher than 10 kW. After the High Power Lab was established in 1993, research projects included power factor correction and soft-switching PWM converters.

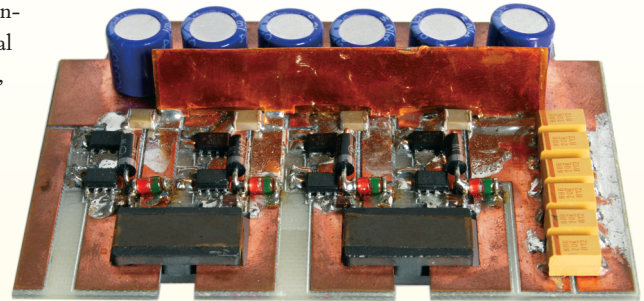
PEBB — The Office of Naval Research (ONR) sponsored many projects from 1995-2000 under the Power Electronics Building Blocks (PEBB) Program. This multi-year effort involved researchers from several departments at Virginia Tech, University of Wisconsin-Madison, Rensselaer Polytechnic Institute, and North Carolina A&T State University. Research on this modular concept and breakthrough technology developed into the IPEM under CPES's direction and continues today. The ONR PEBB effort has sponsored more than 100 research projects with a total of \$65 million of funding to date.

Aircraft — With funding from Schneider Toshiba Inverter Europe and Thales Avionics Electrical Systems, VPEC pursued research on aircraft-related power systems in the late 1990s. The Center researchers worked on multi-pulse ac-dc power conversion by developing 18-pulse autotransformer rectifier units (ATRU). ATRU converters have been adopted in low power appliance applications acting as passive filters for six-pulse diode bridge rectifiers.

HISTORY

ABOUT CPES

The VRM Consortium — From 1985 to 1997 computer speeds grew from 16 MHz to 200 MHz. VPEC formed the Voltage Regulator Module (VRM) consortium in 1997 to pursue development of the next breakthrough. The original consortium members included Intel, International Rectifier, Texas Instruments, National Semiconductor, and SGS Thomson. Within the first six months of beginning the research (started in 1997), VPEC developed a multi-phase voltage regulator module based on parallel multiple buck converter cells. The voltage regulator was smaller, faster, and scalable to suit new generations of processors with ever-increasing current consumption, clockrate and stringent voltage regulations. Today, every microprocessor is powered with the CPES-developed multi-phase voltage regulator modules. Today, over 25 patents have been generated to support the commercialization of this technology.



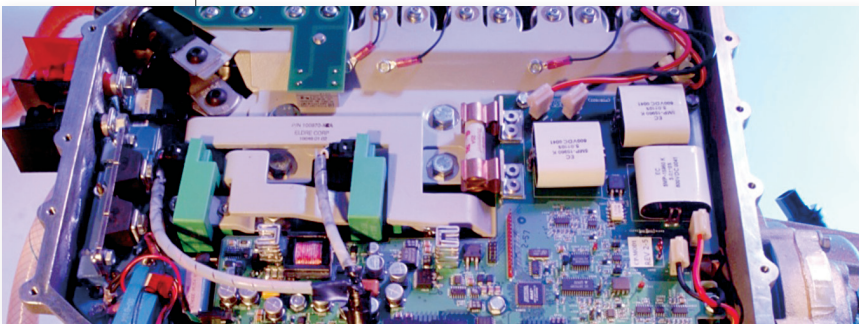
CPES 4-phase VRM

SMES program — Superconducting magnetic energy storage (SMES) is a way of storing energy in a magnetic field. It could be used to help stabilize power grids, among other things.

ONR funded VPEC in 1997 to pursue research targeted at high performance, high power applications. VPEC subsequently developed a 200 kVA chopper-inverter prototype circuit. This system demonstrated the energy storage and transfer

properties of superconducting magnetic storage systems and how they can be integrated into the utility grid to suppress fast transient surge and sag.

The technology was later transferred to Babcock and Wilcox for construction of a 30 MW system. Unfortunately, this project was terminated in the middle of the construction effort.



Fuel cells — Sponsored by Ford under DOE funding, VPEC researchers in 1997 developed a bi-directional dc-dc converter technique for use in fuel cell-powered hybrid electric vehicles. The bi-directional full-bridge dc-dc converter incorporated unified soft-switching schemes effective for power flow in both directions. Together with the control techniques developed by VPEC, it achieved high efficiency and reliable operation. This particular design was patented and commercialized later on by Ballard in every fuel cell test vehicle.



CPES developed a dc-dc converter to provide power to the fuel cell. Bottom: A fuel-cell vehicle.

GET THE DETAILS!

Read more about early history
on the CPES website
www.cpes.vt.edu/public/history.php



The ERC decade

By the 1990s, VPEC was already one of the world's largest power electronics research centers. In 1996, VPEC teamed with the Wisconsin Power Electronics Center of the University of Wisconsin and the Power Semiconductor Research Center (PSRC) of North Carolina State University to submit its first ERC proposal to NSF. The team made it to the final proposal stage and was invited to host an NSF site visit.

In 1998, VPEC teamed with the University of Wisconsin-Madison, Rensselaer Polytechnic Institute, North Carolina A&T State University, and the University of Puerto Rico-Mayaguez to submit its second ERC proposal to NSF. Subsequently, CPES was awarded a ten-year \$30.4 million cooperative agreement from the NSF ERC program to transform VPEC into CPES, with headquarters at Virginia Tech. The funding was renewed for a second five years, enabling the center to develop breakthrough technologies in many areas.

Enabling technology — CPES was founded to advance an enabling technology: the IPEM and integrated power electronics systems. Initially, efforts were focused on the development of the IPEM and the integration technology needed for IPEM-based systems. As IPEMs were developed and commercialized, the research team converged in supporting IPEM synthesis and

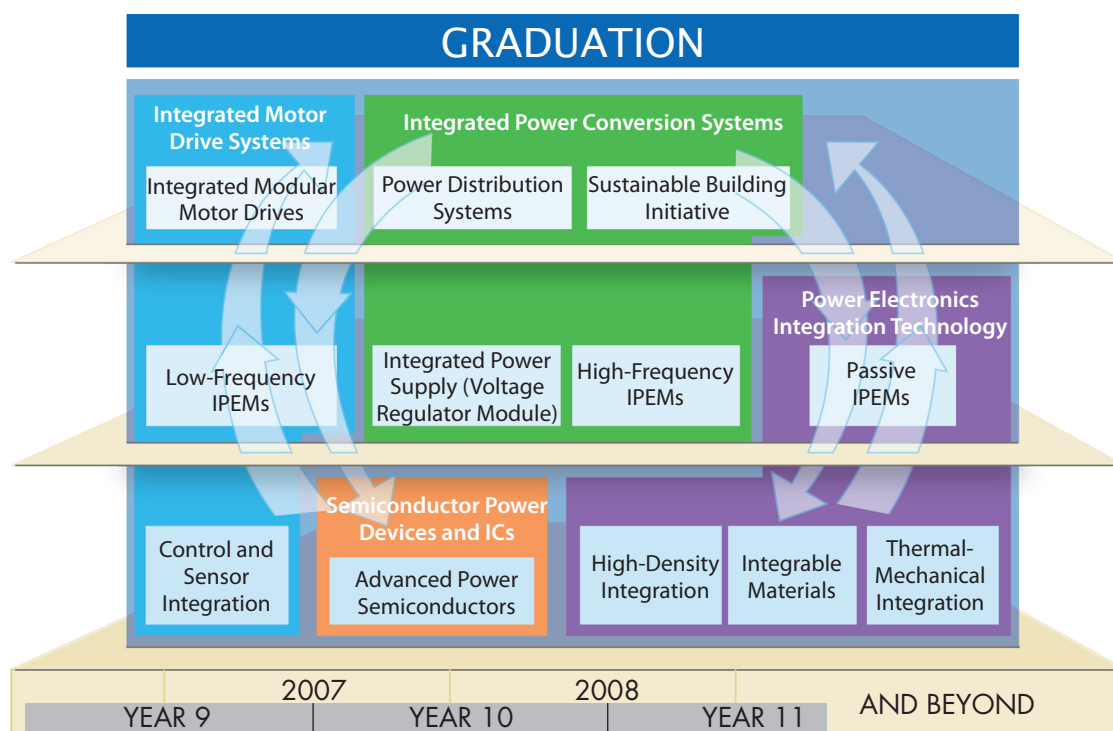
the integration of IPEMs with their intended applications such as integrated power supplies for microprocessor, motor, and converter integration.

Fundamental knowledge — IPEM enabling technology could not progress without advances in fundamental knowledge, which initially included semiconductor devices and packaging. As the technology developed, control and sensor integration were addressed, then materials and thermal-mechanical integration issues.

Engineered systems — Throughout the 10 ERC years, the CPES testbeds and applications concentrated on distributed power systems and motor drives: the two areas of expertise at Virginia Tech and the University of Wisconsin. Once the IPEMs were demonstrated, engineered systems research concentrated on a power conversion system. Post-ERC efforts continue in that area of expertise, but also expand to include more generic sustainable building technology and high-power applications, targeting the use of alternative energy and smart utility grids.

By the end of the ERC funding, CPES research was progressing in four general areas; integrated motor drive systems, integrated power conversion systems, semiconductor power devices and ICs, and power electronics integration technology.

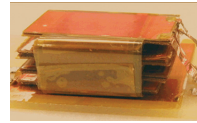
RESEARCH THRUSTS GROUPED INTO AREAS AT GRADUATION



HISTORY

KEY BREAKTHROUGHS

Electromagnetic interference — With ever increasing power density and switching frequency of power electronics equipment, electromagnetic interference (EMI) becomes an important concern. A good EMI filter is essential for every power converter circuit. However, high-frequency performance of EMI filters is affected by the parasitics associated with non-ideal components, referred to as “self parasitics,” and parasitics due to the undesirable electromagnetic field coupling between components, referred to as “mutual parasitics.” CPES researchers first identified the key mutual



First integrated EMI filter

parasitics detrimental to EMI noises, and proposed cancellation techniques for these unwanted field couplings. CPES researchers then developed innovative techniques that mitigate the unwanted effects associated with the self parasitics. These solutions have led to more than 30 times improvement of the differential mode and the common mode noises.

This latter work was recognized as the Best Transaction paper in 2006 by the *IEEE Transactions on Power Electronics*. The work has now been extended to address system-level EMI issues.

Integrated bus filters for EMI containment — CPES demonstrated a major breakthrough in electromagnetic noise containment by pioneering the concept of integrated bus filters, based on transmission line principles. Combined with a filter IPEM, the development enables the construction of a filter IPEM with a cut-off band from around 100 kHz to 100 MHz.

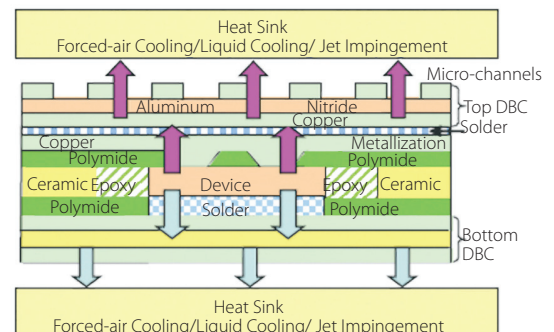
Improving heat removal — CPES demonstrated a process for integrating micro-channels with semiconductor die to improve heat removal at the die level.

Integrated thermal management — CPES demonstrated the feasibility of integrated thermal management by embedding fluidic channels in the IPEM structure.

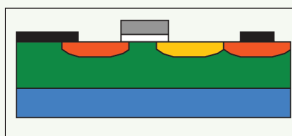
Electric water pump drive — CPES developed an automotive electric water pump drive that incorporates a permanent magnet motor, IPEM-based controller, and the pump impeller into an integrated package that uses the pumped coolant to cool both the motor and the power electronics.

Double-sided cooling — CPES developed, analyzed, and demonstrated the concept of using miniature heat pipes to achieve efficient double-sided cooling of IPEMs.

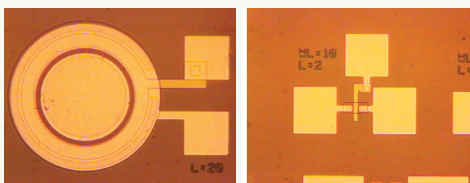
Lateral structure for blocking voltage of 50-80 V CPES developed a novel silicon lateral trench RESURF MOSFET structure that has been projected to have a specific on-resistance close to the ideal value for blocking voltage in the 50-80 V range.



Concept of double-sided cooling for IPEM



Schematic cross-section of the ion-implanted, enhancement mode GaN MOSFET.



Microphotographs of circular and linear devices.

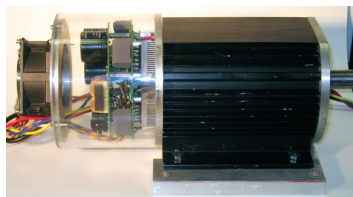
GaN device for bidirectional switch — Most, if not all, modern power devices and ICs are unidirectional and can only block voltage in one polarity. CPES developed gallium nitride (GaN) device technology that led us to identify a high-voltage MOS gate-controlled, bidirectional switch as the basic device building block for power ICs. Performance of the GaN power switching device is expected to be 100 times higher than that of a silicon device. It should improve system efficiency and increase power density, while simplifying power electronics circuit design. Successful commercialization of these GaN power ICs will allow power electronics deployment in applications that were not possible with silicon power devices and ICs.

Replacing conventional wirebond — CPES developed several key technologies replacing the conventional wirebond with direct bonding, such as flip-chip-on-flex and embedded power technology. These integration approaches feature much reduced interconnect parasitics, improved thermal management due to double-sided cooling, and improved opportunities for functional integration.

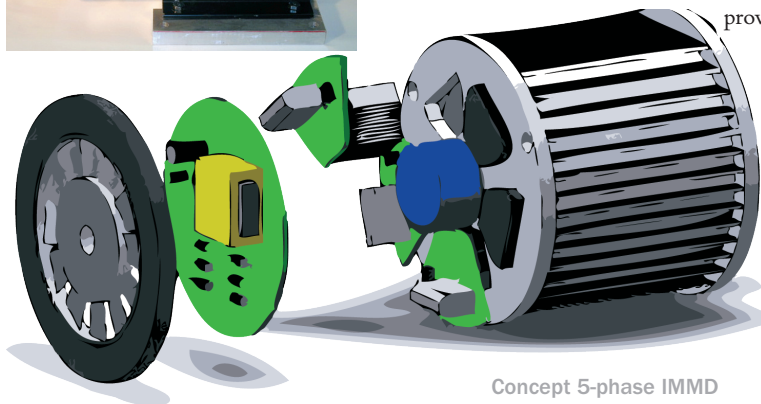
Inverter immune to shoot-through failure — In motor drives, a new phase-leg building-block topology for dc-ac power inverter circuits was invented that is inherently immune to shoot-through failures — the destructive electrical failure mode known to threaten conventional voltage-source inverters since they were first developed nearly 100 years ago. The new phase-leg topology also eliminates the need for dead-time control that is used widely in conventional inverters. This makes it easier to deliver high performance sinusoidal control of ac machine drives down to very low speeds.

Active thermal control techniques — Active thermal control techniques have been developed that act to limit the size of temperature excursions in power modules during normal operation. This provides opportunities to significantly improve the reliability of power electronics because of the serious detrimental impact of thermal cycling on mechanical fatigue and failures inside power module packages.

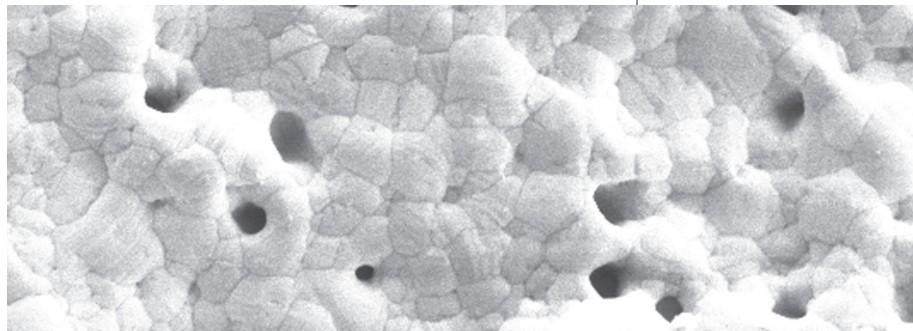
Integrated modular motor drives — CPES pioneered new architecture for future ac machine drives, known as integrated modular motor drives (IMMDs). IMMDs take drive integration concepts to a new level by integrating the power electronics and controller directly into the motor housing.



Integrated modular 5-phase motor drive



Concept 5-phase IMMD



ABOVE: A paste made from silver nano-particles is used to attach components resulting in much improved thermal management of integrated modules.

Sintering nanoscale particles — CPES materials research made great strides in understanding the sintering mechanism of nanoscale particles; an in-depth knowledge has been gained on competing physical processes between coagulation and coalescence aggregation of nanoparticles. This understanding led to the development of a nanoscale silver paste as an alternative lead-free die-attach material for interconnecting semiconductor devices and a multiferroic nanocomposite for integrating passive elements.

Small, flat motor for disc drives — Research on modular permanent magnet motors led to a new concept for a small, flat motor that is an attractive candidate for computer disc drives. The motor has an axial-flux configuration that evolved from a radial-flux design distinguished by its use of sinusoidally-shaped stator pole faces. The topology is compatible with high-volume manufacturing and has fewer parts than the disc drive motor commonly used today.

Improved EMI analysis — Researchers from the University of Padova in Italy collaborated with CPES to develop a continuous wavelet transform to study EMI phenomena. The conventional method of analyzing signals in the frequency domain by using discrete Fourier transform provides complete information. However, the new technique offers better quantification of the frequency content variation during significant transients and shows how the harmonic peaks evolve in time. The deeper understanding of the evolution of the spectra can make it easier to provide the optimized EMI reduction or filter design.

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FACULTY

Fred C. Lee Director



Fred C. Lee is a University Distinguished Professor at Virginia Tech and Director of the Center for Power Electronics Systems (CPES). Prior to CPES, Lee was the founder and director of the Virginia Power Electronics Center (VPEC), one of the largest university-based power electronics research centers in the country.

Lee's research interests include high-frequency power conversion, distributed power systems, renewable energy, power quality, high frequency magnetics, high-density electronics packaging and integration, and modeling and control. Lee holds 69 U.S. patents, and has published 236 journal articles and more than 585 refereed technical papers. During his tenure at Virginia Tech, Lee has supervised to completion 71 Ph.D. and 80 Master's students.

Lee was a recipient of the Society of Automotive Engineering's Ralph R. Teeter Education Award in 1985, became a Fellow of the IEEE and a recipient of the William E. Newell Power Electronics Award in 1989, Virginia Tech's Alumni Award for Research Excellence in 1990, the College of Engineering Dean's Award for Excellence

in Research in 1997, the Arthur E. Fury Award for Leadership and Innovation in 1998, the honorary Sun Yuen Chuan Chair Professor at National Tsinghua University, Taiwan, in 2001, the Outstanding Alumni Award from National Cheng Kung University in 2004, and the Ernst-Blickle Award for achievement in the field of power electronics in 2005.

He has received honorary professorships from Shanghai University of Technology, Shanghai Railroad and Technology Institute, University of Nanjing Aeronautical Institute, Zhejiang University, Harbin Institute of Technology, Huazhong University of Science and Technology, Tsinghua University, Xi'an Jiaotong University, Beijing Jiaotong University, and Hefei Institute of Technology.

Lee has served as president of the IEEE Power Electronics Society (1993-94), and a founder and Chairman of the Board for VPT, Inc. (1993-2009). He currently serves on the Board of Directors for Delta Electronics, Inc., the Delta Environment and Education Foundation, and Neo Energy Microelectronics.

Fred C. Lee received his B.S. degree in electrical engineering from the National Cheng Kung University in Taiwan in 1968, and his M.S. and Ph.D. degrees in electrical engineering from Duke University in 1972 and 1974, respectively. He was named to the National Academy of Engineering (NAE) in 2011.

Paolo Mattavelli



Paolo Mattavelli is a professor of electrical engineering at Virginia Tech. His research interests include analysis, modeling and control of power converters, digital

control techniques for power electronic circuits, renewable energy systems, and grid-connected converters for power quality and power systems applications.

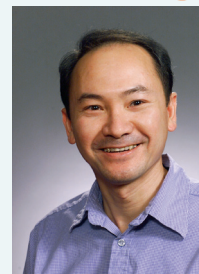
Mattavelli came to Virginia Tech in 2010, after serving five years as an associate professor of electronics at the University of Padova in Vicenza, Italy, where he had earlier served as a researcher (1995-

2001). From 2001 to 2005, Mattavelli was at the University of Udine, Italy, where he founded and led the Power Electronics Laboratory of the DIEGM. From 2002 to 2005, he was an associate professor of electronics there.

Since 2003, he has served as an Associate Editor for *IEEE Transactions on Power Electronics*. He is also the IPCC Paper Review Chair for *IEEE Transactions on Industry Applications* and a Member-at-Large of PELS Adcom. In 2005 and 2006, he received the Prize Paper Award in the *IEEE Transactions on Power Electronics*.

Mattavelli received his M.S. and Ph.D. degrees in electrical engineering from the University of Padova in 1992 and 1995, respectively.

Khai Ngo



Khai Ngo is an electrical engineering professor. His key research interests are in pursuing technologies for integration and packaging of power passive and active

components to realize building blocks for power electronic systems. He teaches courses in electronics, energy systems, power electronics, packaging, and integrated product-process design.

Ngo came to Virginia Tech in 2006 after serving on the electrical and computer engineering faculty at the University of Florida in Gainesville for eight

Dushan Boroyevich Co-Director



Dushan Boroyevich is the American Electric Power Professor at Virginia Tech and CPES co-director. He has led numerous research projects in the areas of multi-phase power conversion, electronic power distribution systems, modeling and control, and multi-disciplinary design optimization.

He developed a comprehensive geometric approach to modeling and control of high-frequency switching power converters, which is widely used for the analysis, design, and control of multi-phase ac power conversion systems. He has advised more than 20 Ph.D. and almost 30 M.S. students to graduation and co-authored with them over 400 technical publications.

Boroyevich joined Virginia Tech in 1990 as an associate professor, and in 1996 became associate director of Virginia Power Electronics Center that was founded by Fred Lee 10 years earlier. In 1998, Lee and Boroyevich

led the team of faculty from Virginia Tech, University of Wisconsin-Madison, Rensselaer Polytechnic Institute, University of Puerto Rico-Mayaguez, and North Carolina A&T State University to win the U.S. National Science Foundation funding for the first national engineering research center in the area of power electronics.

Prior to joining Virginia Tech, Boroyevich was an assistant professor at the University of Novi Sad in what was then Yugoslavia. While there, he founded the power and industrial electronics research and education programs.

Boroyevich is a Fellow of the IEEE and recipient of the IEEE William E. Newell Power Electronics Technical Field Award. He received the Award for Outstanding Achievements and Service to Profession by the European Power Electronics and Motion Control Council, four prize paper awards, and several awards for excellence in research and teaching at Virginia Tech.

He earned a Dipl. Ing. degree from the University of Belgrade in 1976 and an M.S. degree from the University of Novi Sad in 1982, both in electrical engineering. He obtained a Ph.D. degree in power electronics in 1986 from Virginia Tech. Boroyevich is currently the President of IEEE Power Electronics Society.

years. Prior to that, he worked at the General Electric Corporate Research and Development Center in Schenectady, New York, where he worked as a Member of the Technical Staff.

Ngo received the B.S. degree from California State Polytechnic University, Pomona, in 1979, and the M.S. and Ph.D. degrees from the California Institute of Technology, in 1980 and 1984, respectively, all in electrical and electronics engineering.

AFFILIATE MEMBER

G.Q. Lu



G.Q. Lu is a professor of materials science engineering and electrical engineering at Virginia Tech. His research interests are in packaging of microelectronics and power electronics, reliability of electronic components and systems, processing of electronic, magnetic, and dielectric materials, and sintering of metal and/or ceramic materials.

In 2007 his invention of nanoTach was named one of the 100 top inventions of 2007 by *R&D Magazine*. NanoTach is a nanoparticle paste made of silver for interconnecting high-power electronic devices.

Lu received a double-major B.S. degree in physics and materials science and engineering from Carnegie-Mellon University in 1984 and M.S. and Ph.D. degrees in applied physics from Harvard University in 1990. Lu came to Virginia Tech in 1992 after serving two years as a staff engineer at ALCOA Electronic Packaging, Inc.

RESEARCH

PUBLICATIONS

CPES Publication Series

Prior to the establishment of CPES, VPEC (Virginia Power Electronics Center) had compiled a publication series to capture important research and development. The effort continued with CPES and today, the series include:

Volume I High-Frequency Resonant, Quasi-Resonant, and Multi-Resonant Converters (1989)

Volume II Modeling, Analysis, and Design of PWM Converters (1990)

Volume III Power Devices and their Applications (1991)

Volume IV High-Frequency Resonant and Soft-Switching PWM Converters (1992)

Volume V Switching Rectifiers for Power Factor Correction (1994)

Volume VI Power Electronics Components and Circuit Modeling and Analysis (1995)

Volume VII Advanced Power Conversion Techniques (1995)

Volume VIII Converters and Distributed Power Systems (1995)

Volume IX Low Voltage Power Conversion and Distributed Power Systems (2000)

Volume X Integrated Power Electronics Module -- a Building Block Concept for System Integration (2000)

Volume XI Advanced Soft-Switching Techniques, Device and Circuit Applications (2000)

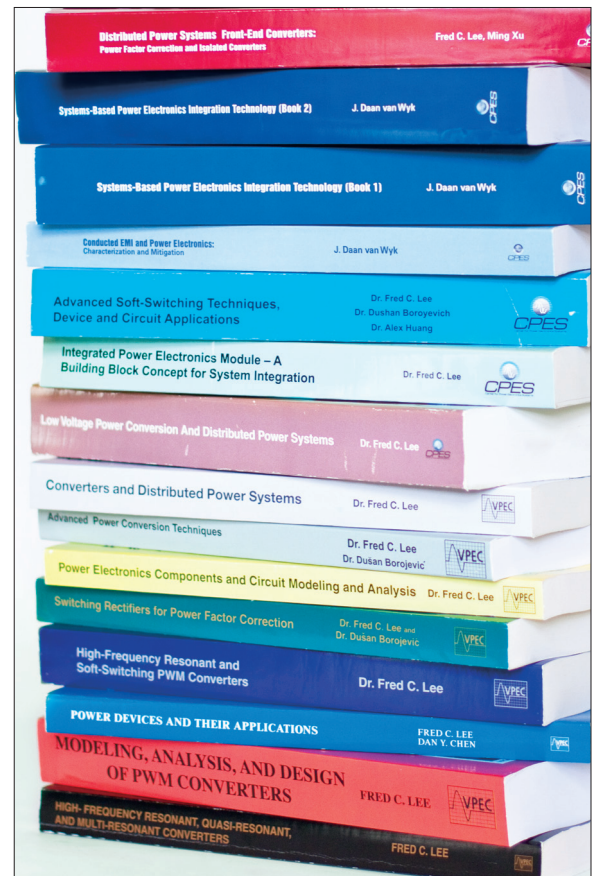
Volume XII Conducted EMI and Power Electronics: Characterization and Mitigation (2008)

Volume XIII (Book 1) Systems-Based Power Electronics Integration Technology (2008)

Volume XIII (Book 2) Systems-Based Power Electronics Integration Technology (2008)

Volume XIV Distributed Power Systems Front End Converters: Power Factor Correction and Isolated Converters (2008)

Volume XV Distributed Power Systems: Point of Load Converters (2008)



Additional volumes will cover high power, motor drives, and semiconductor power devices and ICs.

Through the years, CPES faculty has authored books and textbooks, as well as served as editor and co-editors of special IEEE publications. These include:

June 2001: "Special Issue of the Proceedings of IEEE on Power Electronics Technology: Present Trends and Future Developments," CPES-VT professors, Dushan Boroyevich, Daan van Wyk, Fred C. Lee served as co-editors.



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CPES has produced 118 dissertations, 141 theses, and over 3000 publications, 77 patents, and 195 invention disclosures.

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