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NSF Center For Grid-Connected Advanced Power Electronic Systems Accelerates Adoption Of Power Electronics In The Electric Grid

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The National Science Foundation (NSF) Center for GRid-connected Advanced Power Electronic Systems (GRAPES) is a center of excellence devoted to investigating new technologies, algorithms, software, and deployment strategies involving power electronic systems for the nation's electric power grid. GRAPES is an Industry/University Cooperative Research Center or I/UCRC and the only NSF I/UCRC focused on grid-connected power electronics. As an I/UCRC, research support is derived mostly from membership fees, while administrative costs are supported by NSF.

GRAPES was established by the University of Arkansas (UA) and the University of South Carolina (USC) and funded by NSF to perform research and transfer innovative technologies related to the improvement of the nation's electric grid to industry. The mission of this center is to accelerate the adoption and insertion of power electronics into the electric grid in order to improve system stability, flexibility, robustness, and economy by focusing on several areas of research and technology transfer.

GRAPES Core Values And Mission

The faculty members at USC and UA have worked together for over a decade in one capacity or another. This relationship has been proved successful over time and leads to some key shared core values. It is our hope that our industry members will view these core values as additional assets to our relationships knowing that they can count on these characteristics in our dealings with one another.

As an organization GRAPES' core values revolve around high levels of collaboration; education and professional development of engineers who understand the importance of the insertion of power electronics into the future power grid; and commitment to acceleration of the growth of power electronics. Furthermore, GRAPES is concerned with the engagement and understanding of utility and industrial customer needs.

GRAPES strives to help the power electronics field realize three specific goals. One, it aims to develop new technologies for advanced power electronic systems in the areas supporting grid-connected, distributed energy resources, power steering and routing devices, and intelligent load-side devices. Two, it seeks to develop the software and tools for controlling embedded- and grid-connected power electronics to benefit the grid as well as to control loads. And finally, it serves to educate engineers who understand the power electronic technologies important to members.

The specific projects associated with these areas of research will be discussed in this article. But first, to provide a better sense of why and how this research is being carried out, we will begin with a discussion of GRAPES' guiding principles. The core values and mission of the organization influence the types of research undertaken as well as the manner in which this work is conducted. We'll also introduce the lead researchers and industrial organizations who participate in GRAPES, strategic areas of focus for the organization, and key collaborative outcomes that are sought. In addition, descriptions of the GRAPES research facilities will highlight the tools available to researchers for conducting the various projects.

GRAPES Academic Researchers

GRAPES currently includes two universities—the University of Arkansas and the University of South Carolina. At the UA, researchers include Dr. Alan Mantooth (executive director), Dr. Roy McCann, Dr. Juan Balda (UA site director) and Dr. Simon Ang. Meanwhile at USC, the researchers are Dr. Roger Dougal (co-director and USC site director), Dr. Herbert Ginn, Dr. Charlie Brice, Enrico Santi and Dr. June Shin. These researchers are supported by several staff members. Among them are Mr. T. A. Walton (managing director), Mrs. Kim Gillow (program manager), Mr. Richard Smart (program manager) and Mrs. Hope Johnson (program administrator).

GRAPES researchers and staff.

GRAPES Industrial Advisory Board Members

GRAPES research is primarily funded by the pooled membership fees of our member companies. Research directions and priorities are set by our Industrial Advisory Board (IAB) members, who represent the member companies. The IAB meets face-to-face semi-annually and via webinars quarterly. Our current members represent power utilities, component manufacturers, systems manufacturers, and collaborative research institutes. Current IAB members include:

- Electric Cooperatives of Arkansas
- American Electric Power (AEP)
- Arkansas Power Electronics International (APEI)
- Arkansas Public Service Commission
- Electric Power Research Institute (EPRI)
- Central Electric Power Cooperative
- Koontz Electric Company
- Entergy
- Industrial Technology Research Institute (ITRI)
- Eaton
- Rohm Semiconductor
- Southern Company
- Southwest Power Pool (SPP)

GRAPES Strategic Focus Areas

Consistently advancing power electronics technology involves many aspects of engineering including software, hardware, prototyping, analysis, design, modeling, simulation, etc. GRAPES strives to advance the state of the art in several areas:

- Distributed energy resource management
- Power electronic systems
- Demand-side management
- Power flow control and
- Power electronic modules.

However, it is not only the technology that is being advanced. The organization also strives to produce exceptional students who are highly educated in power systems and power electronics at all degree levels.

Key Outcomes

Research is conducted with four collaborative outcomes in mind. One is the development of new technologies for advanced power electronic systems in the areas supporting grid-connected distributed energy resources, power steering and routing devices, and intelligent load-side devices. Another is the creation of technology awareness and the promotion of adoption by members. Research is also intended to produce software and tools for controlling embedded- and grid-connected power electronics to benefit the grid as well as controlled loads. And finally, GRAPES should produce engineers who understand the power electronic technologies important to the member companies.

Facilities

GRAPES-USC facilities include an Energy Routing Lab equipped with nine Power Electronics Building Blocks (PEBBs) which are configured as multipurpose bi-directional power converters. Each PEBB is rated at 175 kVA and 480 V, and contains a custom-made software-reconfigurable controller that permits the modules to function in modes such as ac-dc, dc-dc, dc-ac or ac-ac power conversions. The modules are configured to represent larger systems, including configurations that recycle the power within the laboratory. This capability permits operation at higher powers than would otherwise be possible with the installed capacity.

The Power Electronics Lab is equipped to characterize power electronic devices and fabricate power converters. The lab contains cryogenic test stands for power electronics, high-speed test and measurement instrumentation including wideband (gigahertz) arbitrary waveform generators, and facilities for fabrication of printed circuit boards.

The Power Sources Lab has facilities for investigating hybrid power sources (fuel cells, batteries, capacitors, integrated through power converters) and the dc systems and protection associated with those power sources. Additionally USC is home to the Virtual Test Bed (VTB), a suite of software for rapid virtual prototyping of large-scale, multidisciplinary dynamic systems. The VTB is now extended to a set of software tools for rapid definition and preliminary evaluation of early-stage energy system concepts that ensures closure of energy flows across all disciplines.

HIDEC Laboratory staff.

GRAPES-UA facilities include the HIDEC (High Density Electronics Center), a developer of award-winning high-voltage and high-amperage power electronic modules, and NCREPT (National Center for Reliable Electric Power Transmission), a 7000-square foot, $5M, national-caliber power electronic test facility with three 2-MVA distribution-level test circuits. This medium-voltage test facility is capable of 3-phase test circuit regeneration at the 2-MVA level at 480 V, 4.16 kV and 13.8 kV.

NCREPT (National Center for Reliable Electric Power Transmission).

NCREPT also can be reserved (on a fee basis) to support IEEE 1547 and UL 1741 testing of grid-interface equipment, and has successfully supported third-party certifications. In addition, the facility has the capability to test truck bed-mounted equipment within its bays.

Current dc capability is 750 kW and variable-voltage, variable-frequency e-phase power is available at the 750-kVA level. The NCREPT center supports three tiers of service to provide the most economical testing support possible to NCREPT users.

Highlighted Research Focus Areas

One area of focus is power electronic module technologies. These technologies include power packaging for silicon and silicon carbide power devices with a rating above 10 kV that have high-temperature potential and operating reliability and may be combined with intelligent power electronics and control circuits.

The development of a power module layout synthesis CAD tool is another research topic. The purpose of this tool is to enable member companies to improve their throughput in module design. The tool considers the simultaneous tradeoffs between thermal, electrical and mechanical constraints. Also covered in this area are rapid prototyping platforms for digital control of power electronic modules and power conversion building blocks. This tool is being developed with input from member company APEI, which has improved existing designs with use.

GRAPES has several projects outlined below that are classified under power flow control and state estimation with the objectives of enhancing existing transmission, distribution and generation infrastructure through coordination of distribution-level power electronic equipment.

The smart green power node is intended to integrate dc and ac power and load resources, including photovoltaic power sources and energy storage batteries, in residential power systems and manage that power for minimum cost. Extensions of this technology can apply to the industrial and commercial sector. An invention disclosure was filed for this device, and a 3-kW prototype is being developed to facilitate technology transfer.

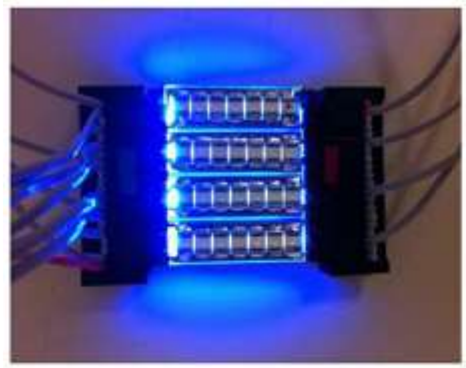
Power flow control and state estimation is meant to enhance existing transmission line and generation infrastructure through coordination of distribution-level power electronic equipment. The goal in developing the solid-state fault current limiter is to increase overall system reliability for distribution and transmission systems.

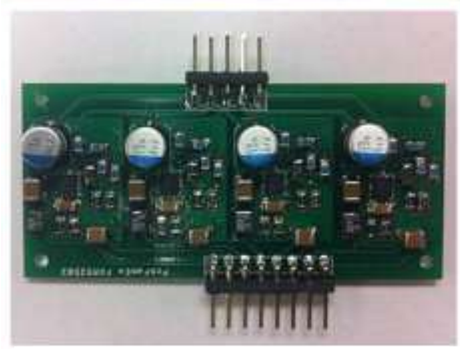
Project: GaN Optical Isolation For Wide-Bandgap Power Electronic Systems

There is a need for power switches that can operate at high voltages, high temperatures and high switching frequencies with low losses. Power devices fabricated from a wide-bandgap material such as SiC or GaN can outperform conventional silicon switchers, due to material property advantages. However, the gate driver must also provide the appropriate protection and sensing functions needed for reliable power converter operation.

The goal of this project is to develop a high-performance optical control for SiC and GaN devices. The optical coupling will be realized using GaN devices that provide superior speed, efficiency and voltage-isolation capability.

An additional advantage for GaN power devices is that the proposed drive can be technologically compatible with GaN processes used for power device fabrication. This project is funded jointly by GRAPES and an NSF Fundamental Research Grant.





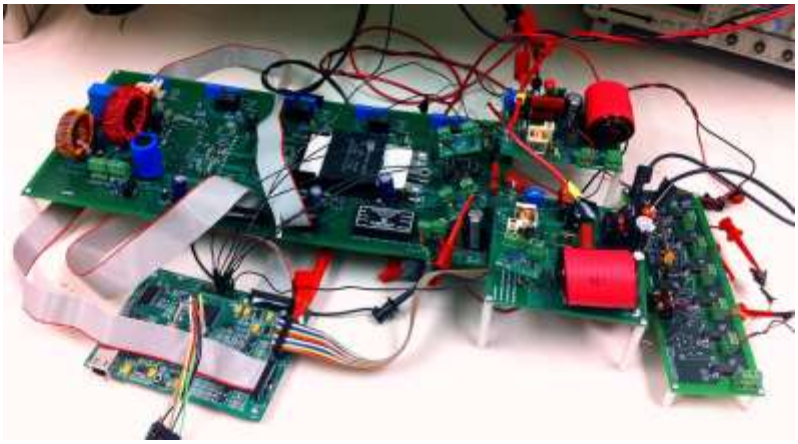
Optically isolated gate driver for wide bandgap high-speed devices.

Project: Modular Multi-level Converter For Transmission-Level Battery Storage

GRAPES is investigating the design of a modular multi-level power converter (MMC) for interfacing battery energy storage to the transmission-level electric utility grid and investigating appropriate energy storage technologies in order to set the parameters for the converter design. Optimization in terms of a multi-stage output topology, switching device selection, and dc-dc battery interface is also planned.

Grid storage technologies will be mainly considered for the functions of frequency regulation, damping of sub-synchronous resonance, voltage support, and reserve capacity. Relative costs, power levels, and charge/discharge profiles will be tabulated and used to establish the range of parameters for a converter that will be suitable for grid-connected energy storage technologies.

Project: Smart Green Power Node—Initial Design And Prototype Build



Prototype of smart green power node.

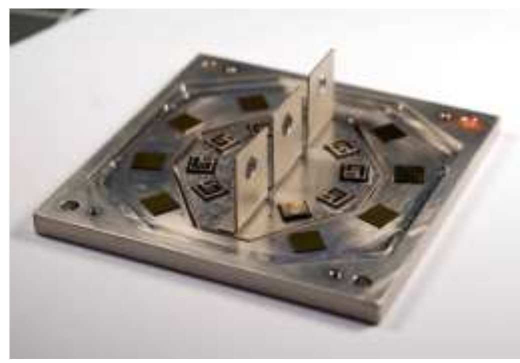
A "green power node" is a system that manages the flow of power between (mostly dc) on-site power resources such as generation, storage, and loads, while it also provides a bidirectional interface to a 240-V single-phase residential grid connection that supports smart grid management. Multiple power sources may connect to this system, including photovoltaic cells, fuel cells, and batteries (stationary, or in a vehicle). The green power node is "smart" in that it manages power flows among all of the devices, as well as to loads and the grid, so as to minimize the cost of electric power.

GRAPES researchers work to provide a general-purpose node to integrate dc and ac power and load resources in residential power systems and to provide standardized grid-side connection, making the system dispatchable from the grid side and uninterruptable on the customer side.

Project: Power Module Packaging

It has long been recognized that higher operating voltages are important for the expansion of power electronics technology. This project concentrates on achieving the high-voltage (10 kV or higher) breakdown requirements of a power electronic module consisting of two power semiconductor devices.

In this project, a new dielectric was developed that demonstrated that this dielectric could increase the breakdown voltage of the power module. Several power module architectures were also developed, including the concept for a double-sided high-voltage power module.



Power module packaging concepts.

Project: Power Module Layout Synthesis Tool

The goal of this project is the design and implementation of a CAD tool that will be used to analyze and optimize the simultaneous electrical, mechanical and thermal issues involved in power module design. This project focuses on the development of algorithms for thermal model abstraction, constrained optimization at the lumped-element level of representation and layout synthesis of power modules accounting for the electrical parasitics, thermal management issues and mechanical constraints imposed by common substrate materials.

The researchers will develop a prototype software package that runs on a Windows-based personal computer or a Linux machine that will determine the optimal geometry of the placement and orientation of the chips on the substrate that meets the electrical performance criteria while minimizing area and material waste in an effort to minimize cost.

Project: Power Dense Power Electronic Interfaces For Distributed Generation

Dense Power Electronic Interfaces project prototype.

Several renewable energy sources (e.g., wind turbines) and non-renewable energy sources (e.g., microturbines using natural gas as fuel), broadly classified as distributed generation sources (DG), produce sinusoidal voltages at frequencies that are different from the grid frequency, or produce dc voltages that are not compatible with grid voltages. Furthermore, most existing topologies use electrolytic capacitors, which are well known to be the weakest link in power converters. Thus, there is a need for power electronic interfaces for connecting DG, which have high power density and are reliable.

The main objectives of this research are to develop indirect matrix converters (IMCs) that are reliable and have high power density to interconnect DG and which require ac-ac conversion or dc-ac conversion with a high-frequency stage. After the development of the SiC-based IMC prototype, another goal of this research is to investigate the viability of using the boosting operation of the IMC.

For Further Information

If you would like to obtain additional information about the GRAPES center, our research efforts, projects or facilities please visit our websites at the links below:

- GRAPES
- USC Power and Energy Systems/VTB
- HIDEC
- NCREPT

Acknowledgement

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About The Authors

T. Avery (T. A.) Walton is the Managing Director for NCREPT and GRAPES I/UCRC. Walton came to the University of Arkansas (UA) in 2008 after a 27-year professional career, which included experience with DuPont Clinical Systems, W.R. Grace Cryovac Division Meat Bag Research and Development, and 23 years with Procter & Gamble Manufacturing Company. Walton's expertise areas include R&D, manufacturing operations, human resources management and sales/customer development.

Walton is a member of the UA Chemical Engineering Academy, Tau Beta Pi, SHRM, the Chancellor's Council on Diversity and the UA Black Alumni Association Board of Directors. He and his wife Vivian sponsor Freshman book scholarships for children of UA system Black Alumni. Walton actively recruits for UA, partnering with the College of Engineering, Graduate Recruiting Office and Honors College in efforts to identify high-potential students in the Arkansas Delta Area.

Walton holds B.S. and M.S. degrees in chemical engineering from UA and performed further studies at Clemson. As a graduate student, Walton studied as an NSF Graduate Fellow, DuPont National Graduate Fellow, and at Clemson as an RC Edwards Graduate Fellow.

H. Alan Mantooth is a Distinguished Professor and the 21st Century Chair in Mixed-Signal IC Design and CAD Electrical Engineering at the University of Arkansas (UA). Mantooth helped establish the National Center for Reliable Electric Power Transmission (NCREPT) at the UA in 2005, for which he serves as Executive Director as well as for two of its constitutive centers of excellence: the NSF I/UCRC for GRid-connected Advanced Power Electronic Systems (GRAPES) and the NSF EPSCoR Vertically-Integrated Center on Transformative Energy Research (VICTER). He also serves as the Director of the NSF EPSCoR GREEN Center for Nanoplasmonic Solar Cell Research.

Mantooth has published over 200 refereed articles on modeling and IC design and is co-author of three books. He holds patents on software architecture and algorithms for modeling tools and has others pending. Mantooth currently serves as Vice-President of Operations for the IEEE Power Electronics Society, is an IEEE Fellow, a member of Tau Beta Pi and Eta Kappa Nu, and a registered professional engineer. Among his accomplishments in industry, Mantooth co-founded Lynguent, an EDA company focused on modeling and simulation tools. Mantooth holds B.S. and M. S. degrees in electrical engineering from UA and a Ph.D. from Georgia Institute of Technology. His interests include HDL-based modeling tools and techniques, analog and mixed-signal IC design and power electronics.

Roger Dougal is the Department Chair, Carolina Distinguished Professor, and Gregory Professor in the Department of Electrical Engineering at the University of South Carolina. Dougal leads the Power and Energy Systems research group, where research principally focuses on power electronics but also encompasses a wide range of associated technologies across a number of engineering departments. Dougal is a member of the Board of Directors of the Electric Ship Research and Development Consortium (ESRDC), and in that capacity he oversees USC's activities related to new power generation, processing, and distribution technologies for ships, and coordination of those activities with other member schools.

Dougal is also Site Director of the NSF-sponsored Industry/University Cooperative Research Center for Grid-connected Advanced Power Electronic Systems. Since 1996, under sponsorship of the Office of Naval Research, Dougal has overseen development of the Virtual Test Bed software, which is a comprehensive simulation and virtual prototyping environment for multidisciplinary dynamic systems.

Dougal currently supervises about a dozen graduate students, several post-doctoral scholars and research faculty, and a number of undergraduate researchers. Dougal holds B.S., M.S. and Ph.D. degrees in electrical engineering from Texas Tech University.

Juan Carlos Balda is the Interim Department Head and a University Professor in the Department of Electrical Engineering at the University of Arkansas (UA). Before coming to UA in 1989, Balda was a visiting Assistant Professor at Clemson University, South Carolina, and prior to that a researcher and a part-time lecturer at the University of Natal. Balda also worked at Hidronor S.A., an electric utility in the southwestern part of Argentina.

His main research interests are power electronics, electric power distribution systems, motor drives and electric power quality. He is a senior member of the IEEE, a member of the Power Electronics and Industry Applications Societies, and the honor society Eta Kappa Nu. He is a faculty advisor to the IEEE Power Electronics Society branch. Balda holds a B.Sc. in electrical engineering from the Universidad Nacional del Sur (Bahía Blanca, Argentina) and a Ph.D. degree in electrical engineering from the University of Natal (Durban, South Africa).