ELECTRIC POWER RESEARCH INSTITUTE

TECHNOLOGY INSIGHTS

A Report from EPRI's Innovation Scouts

GRID-CONNECTED ADVANCED POWER ELECTRONICS SYSTEMS (GRAPES) PROJECTS:

Aiming to Enhance Power System Stability, Flexibility, Robustness, and Economy

THE TECHNOLOGY

Power electronics is a key enabling technology to realize the smart grid. While existing power electronics-based controllers use silicon, wide band gap materials such as silicon carbide (SiC) and gallium nitride (GaN) can improve grid efficiency and performance.

THE VALUE

Power electronics-based controllers enhance the controllability, flexibility, efficiency, stability, robustness, resiliency, and economy of the power grid. These devices also provide innovative, economical methods to integrate renewable energy resources into the grid.

EPRI'S FOCUS

EPRI is monitoring and participating in the power electronics activities of various organizations, including the U.S. Department of Energy, the National Science Foundation, and equipment manufacturers. EPRI continues to assess how relevant advances in adjacent industries can benefit the power grid.

INTRODUCTION

GRid-connected Advanced Power Electronics Systems (GRAPES) aims to "accelerate the adoption and insertion of power electronics into the electric grid in order to improve system stability, flexibility, robustness, and economy" [1]. GRAPES was founded in 2009 under the auspices of the National Science Foundation (NSF) Industry/University Cooperative Research Center (I/U CRC) program. The University of Arkansas (UA), the University of South Carolina (USC), and the University of Wisconsin-Milwaukee (UWM) operate GRAPES.

The NSF program provides funding for administration of the center, but the industry members' annual membership fees pay for the bulk of the research performed as part of the center in a pre-competitive, shared intellectual property arrangement. Currently GRAPES receives funding from 16 industrial and government members, including electric utilities, EPRI, and other industries.

This Technology Insights document summarizes current GRAPES projects.

The project areas reflect the synergies of technological advances and projected industrial needs [1]. Eleven of the 20 projects summarized in this document are fundamental research, and eight projects are more mature and closer to power system applications. One of the projects is currently in the prototype demonstration phase as an EPRI supplemental project. The evolution of technologies in these projects is expected to proceed from fundamental research, to preparation for application, prototype demonstration, and commercialization. Any of the 16 project participants can engage in a commercialization agreement with GRAPES to commercialize GRAPES technologies. The EPRI prototype demonstration project, summarized as the last project of this document, is an example of a project that has successfully proceeded through early phases to prototype demonstration. EPRI anticipates additional successful projects to emerge from the foundational work that the GRAPES team conducts.

The remainder of this document organizes the GRAPES projects according to primary subject areas, including integration of distributed energy resources (DER), microgrids, end-use loads (e.g., data centers), and distribution systems. Additional information on GRAPES is available from the *GRAPES website* [1].

DISTRIBUTED ENERGY RESOURCE (DER) INTEGRATION

Extensive Comparative Study on High Power Inverters Using Various Switching Devices

This GRAPES project addresses the opportunity to improve inverters that help integrate photovoltaics (PV) arrays into the grid (see Figure 1). To comply with total harmonic distortion (THD) grid requirements, Si-based inverters require significant output filtering. This project examines the potential use of wide band gap (i.e., SiC-based) materials in MOSFET-based PV inverters. Fundamental research in this GRAPES project (GR-17-12) will enable PV inverter manufacturers to produce devices with lower losses and improved output voltage quality to meet THD requirements.

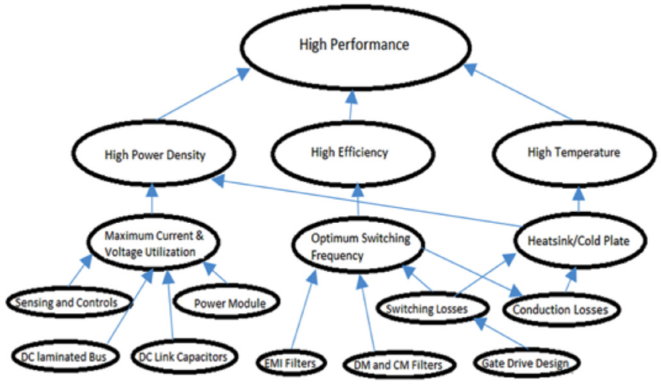

Figure 1 – Comparative study of high power inverters using various switching devices

PV Inverter Control to Sustain High Quality of Service

Proliferation of distributed PV arrays is causing voltage fluctuations on distribution systems resulting in significant customer outage costs. This is occurring because existing voltage regulation on distribution systems was not designed to accommodate two-way, rapidly fluctuating power flows. Fundamental research in this GRAPES project (GR-14-05) is defining ways to plan, control, and coordinate PV systems to enable real-time control to maintain high power quality on the distribution system (see Figure 2). The research includes developing 1) an approach to optimally placing PV systems on distribution systems, 2) an approach for day-ahead optimized scheduling of PV and related systems on distribution feeders, and 3) methods of real-time control for PV inverters. Utilities will realize enhanced PV system control and improved power quality on distribution systems.

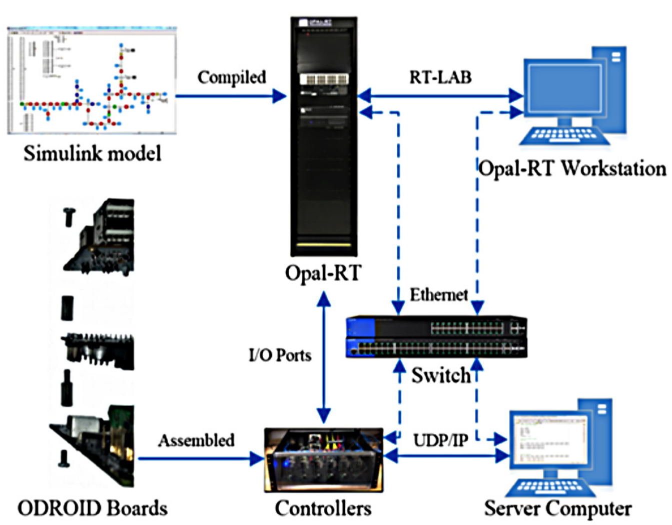

Figure 2 – Laboratory set-up for PV inverter control

Coordinated Optimal Voltage Regulation for Next-Generation Distribution Grids with High Penetration of PV Generation

This GRAPES project (GR-17-08) takes the next step to enhancing voltage control of distributed PV systems (see Figure 3). The project aims to meet three objectives. First, researchers plan to develop a scheme that gathers and uses measurements from smart inverters to partition the distribution system into dynamic voltage reduction zones. Second, the project team will develop a method to inject reactive power by PV inverters in each of these zones. Third, the team will show how smart inverters can better support the grid using model predictive control. Like the previous GRAPES project, this project will further help utilities to optimize voltage regulation on distribution systems with high PV penetration.

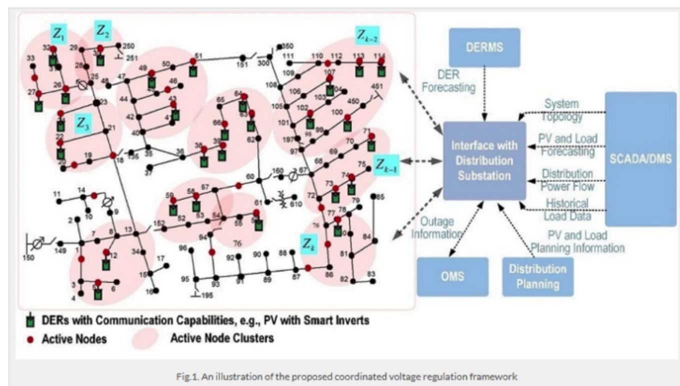

Figure 3 – Proposed coordinated voltage regulation framework

PMU Role in Evaluating PV Generation Impact on Transmission Grid

Installation of large (MW utility-scale) PV arrays can disrupt system protection and compensation on the nearby distribution system. A GRAPES project (GR-17-05) is investigating the use of phasor measurement units (PMUs) – traditionally employed on transmission systems – on distribution systems with large PV installations. The objective is to use the PMU data to mitigate voltage disruptions using power electronics controllers. The project includes proof-of-concept modeling and testing on an actual synchrophasor and PV array at the Arkansas Research and Technology Park. This approach may help utilities mitigate voltage disruptions due to large PV installations on distribution systems.

SiC-Based Direct Power Electronics Interface for Battery Energy Storage System into Medium Voltage Distribution System (13.8 kV)

The conventional topology to interface a battery energy storage system (BESS) with a 13.8-kV medium voltage (MV) includes a step-up transformer to match the BESS and MV voltages. This GRAPES project (GR-17-03) uses a SiC-based inverter to support the voltage differential, and eliminate the transformer. (see Figure 4). The transformerless design is expected to reduce the cost and size of interface components, and increase efficiency by eliminating the transformer losses.

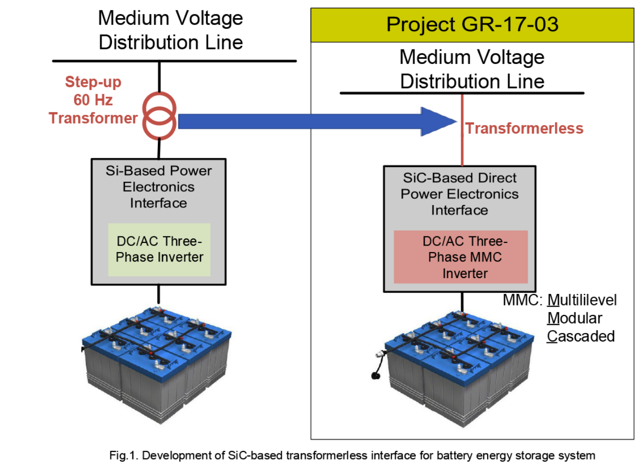

Figure 4 – Development of an SiC-based transformerless interface for a battery energy storage system

MICROGRIDS

Overview

Several GRAPES projects address the challenges and opportunities of microgrids. This section describes GRAPES projects on fault detection and management in microgrids, integration of DER into microgrids, and hybrid microgrids.

Fault Detection and Management Needs Development, and Protective Relaying Methods for Microgrids

This GRAPES project (GR-17-02) addresses the unique challenges of fault detection and management in microgrids. Hardware in the loop (HiL) and power hardware in the loop (PHiL) test platforms have been developed to investigate and implement fault mitigation techniques in AC, DC, and hybrid AC/DC microgrids. Best practices from this research will assist vendors and utilities improve fault detection and response.

Decentralized Energy Management and Robust Decisions for Networked Microgrids in Next-Generation Distribution Systems

This GRAPES project (GR-17-14) investigates the feasibility of implementing a decentralized energy management framework to improve coordination between microgrids and the distribution system (see Figure 5). Utilities and distribution management system vendors may apply the learnings to improve the integration of renewable energy resources, increase economic efficiency, and enhance the overall power system reliability.

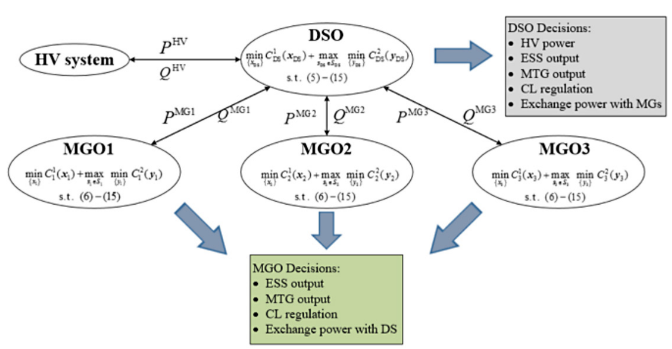

Figure 5 – Coordination between distribution system operators (DSOs) and microgrid operators (MGOs)

Distributed Energy Resources: A Testbed for Distributed Autonomous Control Concepts for High-Power Microgrids

This GRAPES project (GR-17-10) examines distributed control concepts to improve reliability, efficiency, and renewable resource integration in high-power microgrids. The project will simulate wind power, photovoltaics (PV) arrays, and other resources in both grid-connected and islanded modes. Best practices and guidelines developed in this project will help utilities and vendors enhance future microgrid control systems.

Future Hybrid Microgrids

With the proliferation of DC loads, such as data centers, microgrids that efficiently support both conventional AC and emerging DC loads offer potential advantages in energy efficiency, reduced equipment costs (e.g., elimination of adapters to convert AC to DC), and reduced conversion losses. Two GRAPES projects are addressing the feasibility and benefits of hybrid microgrids. Recently completed research examined the coordination of a DC-based battery energy storage unit with a diesel- or natural gas-fueled generator in a hybrid microgrid. Additionally, benefits include improved power quality, increased participation in demand response programs, and improved voltage regulation in the microgrid. Another project (GR-14-08) takes hybrid microgrids further by designing and constructing prototype hybrid microgrids in the MVA power range at the NCREPT test facility.

END-USE LOADS (DATA CENTERS)

Overview

NSF awarded a research grant to the *Center for Energy-Smart Electronic Systems (ES2)* as the prime contractor, the *Power Systems Engineering Research Center (PSERC)*, and GRAPES (I/UCRC) to perform four fundamental research projects and prototype demonstrations on dc-powered data centers.

Evaluation of Wide Bandgap Power Semiconductor Devices for DC-Powered Data Centers

This project evaluates the performance of wide bandgap semiconductor materials (e.g., SiC and GaN) against Si-based converters in dc-powered data centers. The project team will evaluate tradeoffs in efficiency, paralleling of devices, and thermal management across three voltage categories: i) less than 48 Vdc, ii) 48-600 Vdc, and iii) 600-1700 Vdc, and address both current and proposed data center electrical architectures.

Integration of Distributed Energy Sources in DC-Powered Data Centers

A second project evaluates the integration of DER technologies, including PV, wind, fuel cells, combined heat and power (CHP), and electric energy storage into dc-powered data centers (see Figure 6). The geographical location and power rating are the two primary factors that drive which DER technologies are likely to be most competitive. The team is developing a correlation between the DER type and defined data center (load) characteristics. The resulting guidelines are expected to assist optimal integration of DER.

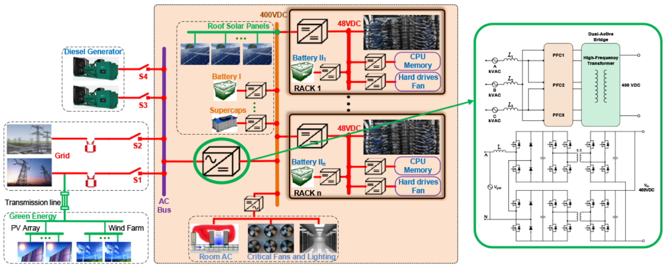

Figure 6 – Integration of DER in dc-powered data centers

Solid-State Technologies for Fault Protection in DC-Powered Data Centers

This project investigates the DC Data Center application performance of Solid-state circuit breaker (SSCB) electronics. Specific project goals include microsecond-based fault isolation, voltage drop during normal operation, overvoltage fault response and recovery, and cost-effective power density (greater than 250 W/in3).

Fast Arc Detection in DC-Powered Data Centers

DC current flow can create an arc hazard when a switch is opened while under load. This project investigates the ability of the SSCB, developed in the previous project, to interrupt and extinguish arcs. The project team is developing a fast, reliable, accurate, and cost-effective arc detection and interruption algorithm for integration with the SSCB controller. This results in reduced component count, increased reliability and will improve the safety of DC-powered systems.

DISTRIBUTION SYSTEMS

Optimized Gate Drivers for High Voltage Power Devices

This project (GR-17-04) optimizes gate driving techniques for 10-kV SiC MOSFETs (see Figure 7). This work will support adoption of SiC-based switches into static synchronous compensators (STATCOMs), static var compensators (SVCs), and other distribution controllers.

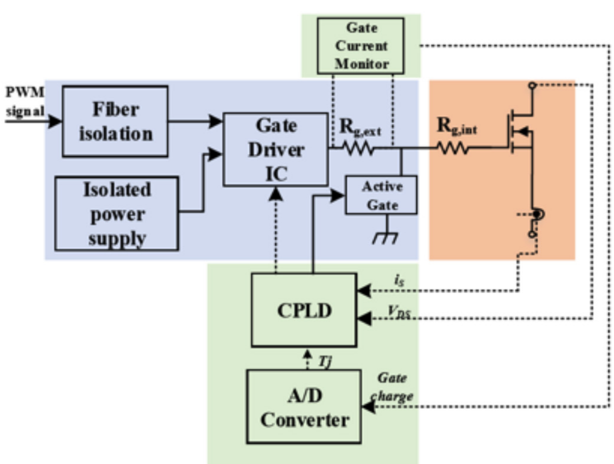

Figure 7 – Optimized gate drivers for high-voltage power devices

Multi-Port, Solid-State Transformer Design and Implementation for Micrograds and Distribution Systems

Advances in power electronics elements can also be applied to development of a multi-port solid-state transformer (MPSST) that enables a single transformer to provide the functions of several conventional transformers. For example, a single multi-port transformer can include multiple output taps to support PV, batteries, electric vehicle (EV) charging, and other grid loads (see Figure 8), while reducing upfront equipment costs, decreasing ongoing maintenance costs, and simplifying installation. Project (GR-17-11) pursues the simulation, modeling, hardware design, prototyping, and experimental testing of a 40-kW, 480-V, 4-port MPSST.

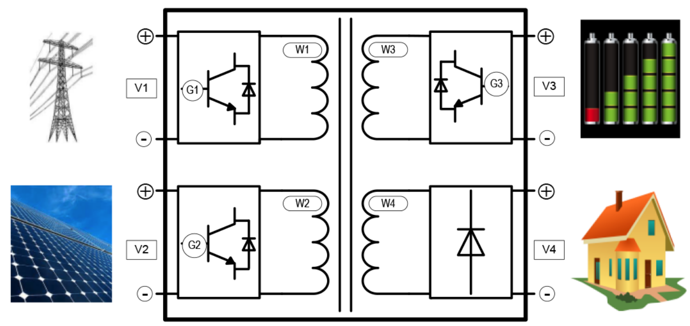

Figure 8 – Multi-Port, Solid-State Transformer

Physics-based Analytical and Compact Modeling of GaN Power Devices for Advanced Power Electronics

The GRAPES project (NSF-15-06) is helping to accelerate development and adoption of GaN-based power electronics, by developing publicly-available, open- access GaN device models that enable device engineers to conduct side-by-side comparisons of GaN- and Si-based devices during design.

Distributed Power Quality Improvement Using Power Electronics and Digital Signal Processing

Enhanced penetration of renewable resources is reducing power quality by inducing voltage sags and swells, which lead to unbalanced currents on distribution feeder lines and in microgrids. Traditionally, utilities have mitigated power quality impacts by introducing static var compensators or other devices at the utility/customer interface on power systems. Project (GR-16-03) is investigating an alternative power quality mitigation technique by simulating the co-location of three devices: a fast compensator to address current sharp edges, a reactive compensator to mitigate reactive current, and a slow compensator to handle low frequency modulation. Next step is to develop a prototype demonstrator for experimental validation.

Mobile Power Substations

In the wake of large-scale outages caused by hurricanes and other events, there is interest in identifying solutions that can boost grid resiliency. GRAPES project (GR-15-03) has developed designs for a mobile distribution substation. This substation may be installed and transported on a single semi-truck (without exceeding max vehicle load limits of 80,000 pounds), function in extreme weather conditions, satisfy IEEE 519-2014 total harmonic distortion limits, and leverage traditional distribution protection equipment. The project also incorporates a solid-state transformer between the medium-voltage (MV) and the low-voltage (LV) networks. Next step is a prototype demonstration.

GRAPES SUCCESS STORY: MEDIUM-VOLTAGE STATIC COMPENSATORS FOR DISTRIBUTION SYSTEMS

Expanding on a 2017 GRAPES project, EPRI is offering a utility member supplemental demonstration project that uses high-voltage (HV) SiC devices (e.g., 10-kV, 6.5-kV, and 3.3-kV SiC MOSFETs by Wolfspeed/Cree) to enable development of direct-connect and "plug-and-play" power electronics systems. Distribution system operators will be able to use and program this system similar to existing shunt capacitor banks and voltage regulators.

The project has the following primary objectives:

- Design a three-phase 13.8-kV, 1-MVA medium-voltage unbalanced-current static compensator (MV-UCSC), with the following characteristics (see Figure 9):
  - Uses HV SiC MOSFETs from Wolfspeed/CREE
  - Fully compensates for upstream negative- and zero-sequence currents
  - Provides up to 10% compensation of feeder reactive power, complementing the operation of shunt capacitor banks in distribution systems
- Fabricate and test at the *NCREPT test facility* only two phases for the designed MV-UCSC. Fabricating a three-phase 13.8-kV, 1-MVA MV-UCSC is not feasible due to a limited budget for materials.

Connecting power electronic converters to distribution systems without step-up transformers requires multi-level converter topologies. Based on a preliminary evaluation of several topologies, the research team at the University of Arkansas, Fayetteville (UAF) has determined that a flying capacitor converter (FCC) topology will be more suitable for a MV-UCSC directly connected to MV distribution systems. The research team will design in detail the FCC topology, assuming the following feeder characteristics:

- Line-to-line rated voltage: 13.8 kV
- Substation rated power: 20 MVA
- Substation power factor: 0.9 lagging power factor (uncompensated)
- Largest current imbalance: 0.15 pu between any two phases

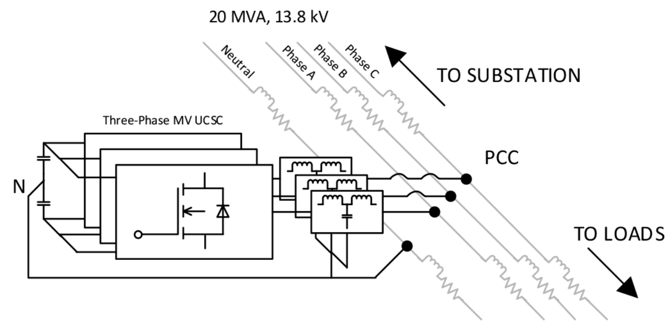

Figure 9 – General schematic of a medium voltage, unbalanced-current static compensator (MV-UCSC) for three-phase four-wire electric power distribution systems (PCC – Point of Common Coupling).

The project team has completed preliminary designs of a three-phase 13.8-kV, 1-MVA MV-UCSC using the FCC topology. One, three-phase design has 11 levels and uses 60 3.3-kV SiC MOSFET modules. A second design has 5 levels and uses 24 10-kV SiC MOSFET modules. Initial estimates of the maximum hard-switching frequency are approximately 2 kHz for the 10-kV devices and 20 kHz for the 3.3-kV devices. At these switching frequencies the estimated maximum system efficiencies are 98.7 % (10-kV devices) and 96.7 % (3.3-kV devices). Designs using 6.5-kV and 1.7-kV SiC MOSFETs will also be considered to select the best power semiconductor device for this MV-UCSC application.

Primary project milestones and deliverables include the following:

- **December 30, 2017:** Selection of the MV SiC MOSFET and final design of the MV-UCSC power stages
- **March 31, 2018:** Design of a submodule assembly
- **June 30, 2018:** Prototyping of two MV-UCSC phases
- **September 30, 2018:** Testing of the MV-UCSC two-phase prototype
- **December 31, 2018:** Final report and proposal to construct a full-size prototype

FOR MORE INFORMATION

Dr. Ram Adapa, *Technical Executive*
Power Delivery and Utilization
650.855.8988, radapa@epri.com

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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com