IV.C.2 Advanced Power Conversion System (PCS) Technologies for High-Megawatt Fuel Cell Power Plants

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Objectives

- Identify advanced technologies that may significantly reduce the cost of the power conversion systems (PCS) required for future high-megawatt fuel cell power plants.
- Determine fuel cell power plant PCS performance requirements, including requirements for interfacing to fuel cell modules and for power grid connectivity.
- Develop simulation models for advanced PCS architectures, circuit topologies, and component technologies and perform simulations required to determine overall cost and performance benefits of advanced technologies.
- Coordinate with related industry and federal government programs to enable the development of advanced high-megawatt PCS technologies necessary to meet the Solid State Energy Conversional Alliance (SECA) and FutureGen PCS goals.

Accomplishments

- High-Megawatt Converters Workshop held at NIST in Gaithersburg, MD on January 24, 2007, included 42 invited participants and 21 invited presenters.
- Industry/government/university consensus reached on the process and parameters for the NIST/DOE advanced PCS technology impact analysis.
- Several approaches identified for reducing the fuel cell power plant PCS cost using silicon-carbide (SiC) power semiconductor devices.
- Simulation models developed for 10 kV SiC power metal-oxide-semiconductor field effect transistors (MOSFETs) and 10 kV SiC junction barrier Schottky diodes to be used for validation and refinement of cost reduction and performance impacts.
- Industry/government/university consensus reached on the formation of a roadmapping committee and interagency task group for high-megawatt PCS technology.

Introduction

High-megawatt PCSs are required to convert the low voltage power produced by fuel cell modules in central station scale plants to the very much higher voltage levels required for delivery to the grid. The SECA megawatt power plant PCS cost goal of $40-$100/kW is generally recognized as a difficult stretch goal that cannot be met with today's technology. To address this challenge, DOE and NIST have entered into an interagency agreement to have NIST lead an effort to evaluate various advanced technology options for the PCS and to identify technologies requiring development to meet the cost and efficiency goals of the SECA central station fuel cell power plant.

Approach

This project aims to evaluate advanced PCS architectures, circuit topologies, and component technologies that may significantly reduce the lifecycle cost of the SECA central station fuel cell power plant. Various PCS approaches that focus on the use of advanced technologies for low-voltage, medium-voltage, and high-power architectures are considered. The advanced component technologies being considered include advanced power semiconductor devices made with the SiC material, advanced nano-crystalline magnetic materials for filters and transformers, advanced capacitor technologies, advanced power electronic component cooling systems, and modular power electronic package and interconnect approaches.

Each PCS approach is being evaluated for its ability to meet the performance requirements of the fuel cell power plant including requirements for interfacing to fuel cell modules and for power grid connectivity, as well as the cost of constructing and maintaining the PCS. The cost and performance estimates are made using tabular spreadsheet calculations where detailed circuit simulations are used to verify and refine the component interaction and system performance impacts used in the spreadsheet calculations. The project thus requires the development of simulation models for advanced PCS architectures, circuit topologies, and component technologies.

The evaluation of the overall impact of advanced PCS technologies requires input from, and coordination with, the broad power electronics community. To initiate this interaction and review the approach being used for the advanced technology impact evaluation, a "*High Megawatt Converter Workshop*" [1] was held at NIST headquarters in Gaithersburg, MD on January 24, 2007. The objectives of the workshop were to exchange information focused on state-of-the-art technologies for high-megawatt PCSs, discuss the merits of proposed approaches to achieving significant cost reduction and improved electrical conversion efficiency, discuss how federal resources could potentially be utilized in a coordinated effort to address these issues, and to discuss the merits of establishing an industry-led roadmap committee to offer guidance that could facilitate the achievement of the desired goals.

Results

High-Megawatt Converter Workshop: The High Megawatt Converter Workshop held at NIST on January 24, 2007 included 42 invited participants and 21 invited presenters. Ten of the presentations described specific technologies deemed to have the potential to reduce PCS cost and seven presentations discussed the common needs for high-megawatt PCSs across industry and government agencies. Open discussion sessions were also held to discuss the specific approach being used for the NIST/DOE Advanced PCS Technology Impact Analysis, and to discuss the merits of forming an interagency task group and an industry roadmap effort for high-megawatt PCS technologies.

Interagency Task Group on High-Megawatt PCS: The High Megawatt Converter Workshop participants agreed that a federal interagency task group for high-megawatt power converter technologies could play an important role in this area. It was also suggested that the Interagency Power Group (IAPG) would be a good organization to host such a task group. Subsequently, during the IAPG Strategic Planning Meeting on April 3, 2007, the IAPG agreed that a reinitiated IAPG Electrical Systems Working Group (ESWG) could serve, in part, as an umbrella organization for the High-Megawatt PCS Interagency Task Group.

Industry Roadmap on High-Megawatt PCS: The High Megawatt Converter Workshop participants agreed that a roadmap process should be initiated to offer guidance for further development of PCSs that could meet the requirements for more cost-effective and more efficient power conversion and a number of those present expressed a willingness to serve on such a committee.

Advanced PCS Technology Impact Analysis: During the High Megawatt Converter Workshop, various aspects of the NIST/DOE Advanced PCS Technology Impact Analysis effort were reviewed including: the overall approach of the study, the current and voltage boundary conditions, the grid-connectivity requirements, fuel cell current regulation and ripple requirements, as well as, the topology and component technologies being considered by the study. Various conversion approaches that focus on the use of advanced technologies for low-voltage, medium-voltage, and high-power architectures were outlined.

Consensus on Impact Analysis Approach: A general consensus was reached on the approach and specifications for the NIST/DOE study as described below:

- Methodology for impact study:
  - Classify power converter architectures and component technologies that may reduce cost
  - Perform tabular calculations of cost for each option using estimated advantages of new technologies
  - Use component modeling and circuit and system simulations to verify and refine calculations
- Consider power electronics and/or transformer up to 18 kV AC and assume transformer from 18 kV AC to transmission level voltage.
- Boundary conditions and performance parameters:
  - Fuel cell stack: center tap ~700 VDC, 1,000 A
  - Individual fuel cell stack current control (may be necessary for fuel cell reliability)
  - Fault tolerant and serviceable
- Converter cost components:
  - Semiconductors
  - Module packaging
  - Interconnects
  - Cooling system
  - Magnetics: filter inductors and high frequency voltage isolation transformers
  - Transformer up to 18 kV
  - Breakers

The initial baseline for the study is a center tapped fuel cell (approximately 700 V DC, 0.6 MW) with a DC-DC converter for fuel cell current regulation, a 480 VAC inverter, and a 60 Hz transformer to raise the output voltage to 18 kV AC. This option is chosen as the baseline because it includes the individual functions necessary to expand to a DC common bus and to high-voltage and/or high-power inverter topologies. The "present lowest-cost" option combines the DC-DC regulator and 480 V AC inverter functions into a single converter stage that uses the "present lowest-cost" switching power device, a 1,200 V insulated gate bipolar transistor (IGBT) module.

Low-voltage PCS inverters: For the low voltage inverter options, advanced semiconductor technologies such as SiC power devices enable the use of higher frequencies that may reduce the cost of passive components. The advanced semiconductor devices may also result in lower switching losses resulting in higher power conversion efficiency and lower cost thermal management systems. SiC power semiconductor devices have recently begun to emerge as commercial products where low current SiC junction barrier Schottky diodes are becoming common place in computer server power-factor-correction circuits. Commercial 1,200 V SiC MOSFET switches and 1,200 V hybrid SiC-junction barrier Schottky/Silicon-IGBT modules are also expected in the near future.

Medium voltage inverters: The second class of power converters being evaluated uses a DC-DC converter to step the voltage up to 6 kV and a medium-voltage inverter is used to produce 4,160 VAC, then a transformer is used to raise the voltage to 18 kV AC. In this case, the DC-DC converter can combine the function of increasing voltage with the function of regulating fuel cell current. The advantage of using a medium-voltage inverter is that it reduces the current for a given power processing level so that a single inverter can be used for multiple fuel cell stacks.

Medium-voltage semiconductors: Various semiconductor options exist for medium-voltage inverters including high voltage (HV)-IGBTs, integrated gate commutated thyristor (IGCTs), and high-voltage SiC devices. Recently, commercial HV-IGBT modules have been introduced to increase the voltage and current level to 6.5 kV, 600A, and commercial 6.5 kV, 3,000 A IGCTs have been introduced that provide improved gate turnoff thyristor (GTO) switching speed using a high current, low-inductance gate drive to switch off the full wafer GTO in unity-gain mode. However, these existing semiconductor devices require the use of multilevel inverters for medium voltage applications. This is due to the lack of voltage margin when using a 6.5 kV switch and, also, to the relatively low switching frequency of the high-voltage silicon devices (<1 kHz). On the other hand, the high-voltage, high-frequency (10 kV, 20 kHz) SiC semiconductor devices currently under development by the Defense Advanced Research Projects Agency (DARPA) High Power Electronics program would enable the use of a single level inverter with a much lower part count and lower filter inductance requirements [2].

High-power architectures: Finally, various power converter architecture options are being evaluated for using a single medium-voltage, high-power inverter for multiple 700 V, 0.6 MW fuel cell stacks. Each architecture option imposes different requirements on the DC-DC converter and DC-AC inverter functions and thus realizes different benefits from advanced semiconductors, magnetics, and capacitors. For example, architectures requiring DC-DC converters with high-voltage gain or high voltage-isolation may also benefit from advanced magnetic materials, which, in effect, step-up the voltage using the high-frequency magnetic components rather than a much larger 60 Hz transformer. In each case, the power converter architecture and component technologies must be considered together to determine the overall benefits to the PCS system and to identify a complete set of advanced technologies required for a given approach.

Consensus on specifications: After the briefing on the approach being considered for the impact study and on the individual power converter technologies, the High-Megawatt Converter Workshop participants were asked during an open discussion session to provide feedback on additional specifications and technologies to be included in the study. The questions posed during this session and the consensus for additional considerations to the impact study are summarized below.

Requested inputs from the workshop participants:

- Preferred high-megawatt architectures and topologies.
- Specifications for filter requirements:
  - Harmonics for power generation connectivity (e.g. IEEE1547).
  - Electromagnetic interference (EMI) requirements.
- Other advanced component technologies:
  - Nano-crystalline magnetic materials for high-gain converters or voltage-isolated converters.
  - Packaging and advanced cooling systems.
  - Interconnects and modularity.
  - Capacitors (Dry Q cap: low cost, low maintenance).

The experts at the workshop recommended that the study be based on the following:

- Specifications for filter requirements:
  - Inverter harmonics requirement: IEEE 519.
  - EMI requirements: Mil STD 461 or equivalent.
- Specifications for fuel cell current regulator:
  - Ripple requirement: <3% for frequencies <1kHz.
- Year 2020 fuel cell voltage may be 2,000 V (center-tap).

Of particular importance is the consensus on the power converter performance requirements and applicable standards. It was also recommended that the study be expanded to include the impact of increased fuel cell stack voltage that is expected to occur by the year 2020.

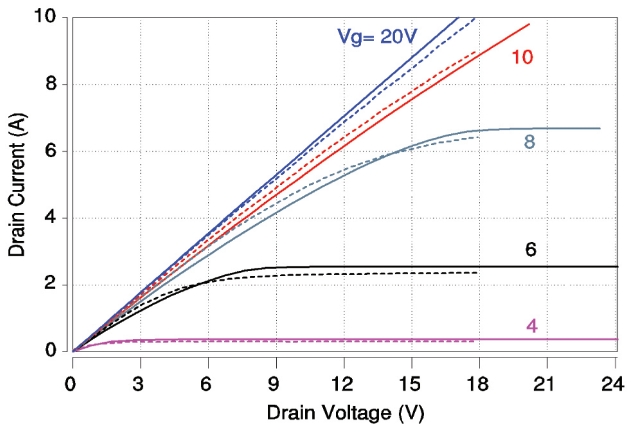

FIGURE 1. Comparison of Measured (Dashed) and Simulated (Solid) Output Characteristics at 125°C for a 5 A, 10 kV SiC MOSFET

Advanced PCS Component Technology Models: Simulation models for advanced PCS architectures, circuit topologies, and component technologies are required for the technology impact evaluation. One of the most potentially revolutionary technologies for high-voltage and high-power conversion systems is power semiconductor devices made with the SiC material. NIST has recently developed models and parameter sets for 1,200 V and 10 kV SiC MOSFETs and junction barrier Schottky diodes to be used in this work. As an example, Figures 1 through 3 show comparisons of the 10 kV SiC power MOSFET and junction barrier Schottky diode models with measured steady-state and transient characteristics [3]. (In general, the high-voltage SiC devices are two orders of magnitude faster than devices made with the conventional silicon material.) The NIST developed models will be used to evaluate the cost and performance advantages of the DC-DC and DC-AC converters identified above [4].

Conclusions and Future Directions

The major effort of this project thus far has been focused on establishing the approach and conditions for the NIST/DOE Advanced PCS Technology Impact Analysis and in initiating the Interagency Task Group on High-Megawatt PCS. The High Megawatt Converter Workshop held at NIST on January 24, 2007, resulted in a consensus on the process and parameters for the NIST/DOE study and the formation of an interagency task group, and on a roadmapping committee for high-megawatt PCSs.

The IAPG Strategic Plan document developed at the IAPG meeting includes plans for reinitiating the ESWG that will host the high-megawatt PCS interagency task group. The points-of-contact and participants from appropriate federal agencies have been identified and

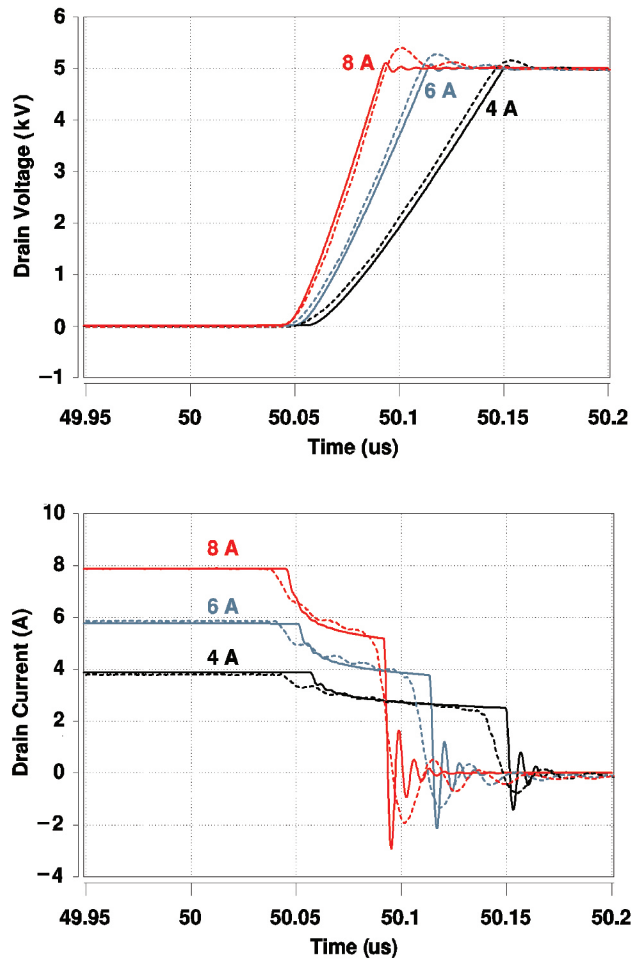

FIGURE 2. Comparison of Measured (Dashed) and Simulated (Solid) Inductive-Load Switching Turn-Off Waveforms at 25°C for a Clamp Voltage of 5 kV and a 5 A, 10 kV SiC MOSFET

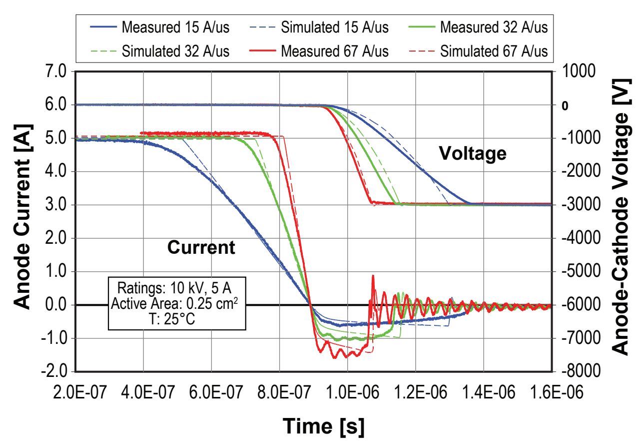

FIGURE 3. Comparison of Measured (Solid) with Simulated (Dashed) Clamped Reverse Recovery Transient Waveforms for a 10 kV, 5 A SiC Junction Barrier Schottky Diode at Three Different Turn-Off Current Ramp Rates (15, 32, and 67 A/us)

a meeting is tentatively planned for September 2007 to begin this activity that will continue in the future.

Simulation models for advanced PCS component technologies and simulation schematics for power DC-DC and DC-AC converters are now under development. Simulations are beginning to be performed and will continue in the future to validate the system impact of the identified advanced PCS component technologies.

FY 2007 Publications/Presentations

1. Proceedings of the High Megawatt Converters Workshop, Jan. 24, 2007, NIST Headquarters, Gaithersburg, MD, www.high-megawatt.nist.gov/workshop-1-24-07/.

2. A. R. Hefner, R. Sei-Hyung, B. A. Hull, D.W. Berning, C. E. Hood, J. M. Ortiz-Rodriguez, A. Rivera-Lopez, T. Duong, A. Akuffo, and M. Hernandez , "Recent Advances in High-Voltage, High-Frequency Silicon-Carbide Power Devices," Proceedings of the 2006 IEEE Industry Applications Society (IAS) Annual Meeting, October 08-12, 2006, Tampa, FL, pp. 330-337.

3. J. M. Ortiz-Rodriguez, T. Duong, A. Rivera-Lopez, and A. R. Hefner, "High-Voltage, High-Frequency SiC Power MOSFETs Model Validation," Proceedings of the 2007 IEEE Power Electronics Specialists Conference (PESC), June 17–21, 2007, Orlando, FL.

4. T. H. Duong, D.W. Berning, A. R. Hefner, and K. M. Smedley, "Long-Term Stability Test System for High-Voltage, High-Frequency SiC Power Devices," Proceedings of the 2007 IEEE Applied Power Electronics Conference (APEC 2007), February 25 – March 1, 2007, Anaheim, CA, pp. 1240-1246.