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High Megawatt Workshop Power Conditioning System

Technology Roadmap
for Increased Power Electronic Grid Applications and Devices

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NIST Headquarters, Gaithersburg MD

Proceedings Prepared By

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List of Abbreviations

AC	Alternating Current
ADEPT	Agile Delivery of Electrical Power Technology
AMDR	Air and Missile Defense Radar
ARRA	American Recovery and Reinvestment Act of 2009
ARPA-E	Advanced Research Project Agency-Energy
BTU	British Thermal Units
CPES	Center for Power Electronics Systems
DC	Direct Current
DOE	Department of Energy
DOD	Department of Defense
DG	Distributed Generation
EPRI	Electric Power Research Institute
ESS	Energy Storage Systems
FIDVR	Resistance to Fault Induced Delayed Voltage Recovery
EIA	Energy Information Agency
FY	Fiscal Year
GaN	Gallium Nitride
GENI	Green Energy Network Integration
GW	Giga Watt
GWh	Giga Watt-hour
HF	High Frequency
HM	High Megawatt
HMW	High Megawatt Workshop
HV	High Voltage
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistor
IOU	Investor Owned Utilities
ISO	Independent System Operator
ITC	Investment Tax Credits
GEN	Generation
JBS	Junction Barrier Schottky
JFET	Junction Field-Effect Transistors
kHz	kilohertz
kV	kilo Volts
kVA	kilo Volt Ampere
kW	kilo Watt
kWh	kilo Watt-hour
LCOE	Least Cost of Electricity
LVRT	Low Voltage Ride Through
m	meter
MEMS	micro electromechanical systems
MOSFET	Metal-Oxide Semiconductor Field-Effect Transistor
MVA	Mega Volt Amperes
MW	Megawatt

MWh	Megawatt hour
NIST	National Institute of Standards and Technology
O&M	Operating and Maintenance
PCS	Power Conditioning System
PEM	Proton Exchange Membrane
PTC	Production Tax Credits
PV	Photovoltaic
RPS	Renewable Portfolio Standards
R&D	Research and Development
Si	Silicon
SiC	Silicon Carbide
SGTO	Super Gate Turnoff Thyristor
SSPS	Solid-State Power Substation
TDS	Traction Drive System
THD	Total Harmonic Distortion
T&D	Transmission and Distribution
US	United States
VAC	Volts AC
VACRMS	Volts AC Root Mean Square
WEG	Worldwide Equipment Guide

1. Summary

On May 24, 2012, 32 invited participants convened in a workshop held at NIST (National Institute of Standards and Technology) headquarters in Gaithersburg, Maryland. Three technical sessions, at which 12 presentations were given, were titled:

- Applications and Drivers for Increasing Grid PCS (Power Conditioning Systems)
- Advanced HM (High Megawatt) PCS Technologies and Approaches
- Technology Development Programs

The complete set of presentations can be viewed or downloaded at the NIST High Megawatt Workshop (HMW) site at http://www.nist.gov/pml/high_megawatt/may-2012_workshop.cfm.

The major conclusions that can be drawn from the presentations and discussions at this Workshop are that:

The existing electrical grid needs replacement of aging components, expansion of capacity to accommodate increased population and increased per capita use of electricity, utilization of advanced PCS to improve transmission efficiencies, initiate some control of power flows, and to better cope with the issues resulting from the increased delivery of intermittent and rapidly fluctuating power from solar and wind generators.

The growing availability of high quality SiC material and SiC–based components and devices has enhanced the capabilities of PCS components such as Schottky diodes, JBS (Junction Barrier Schottky) diodes, JFETs (Junction Field-Effect Transistors). MOSFETs (Metal-Oxide Semiconductor Field-Effect Transistor), and Insulated Gate Bipolar Transistors (IGBT). Many of these devices have capabilities that cannot be achieved with Si-based components. The number, capability, and commercial availability of these products is increasing rapidly at this time and can play a significant role in upgrading the US electrical grid.

This commercial availability of SiC-based components is attributable in large part to the long-term funding of R&D (Research and Development) programs that has been provided by numerous agencies of the Department of Defense (DOD) as well as by other federal agencies including NIST and ARPA-E (Advanced Research Projects Agency-Energy). Much of this R&D has been done by integrated teams that have included private sector companies, national laboratories, and universities.

Additional research and development is needed to improve PCS systems to meet specific DOD operational requirements and ARPA-E goals of ensuring the economic and energy security of the US (United States) and to ensure that the US maintains the technological lead in developing and deploying advanced energy technologies.

2. Introduction

Workshop Structure

The stated objectives of the Workshop were summarized in the invitation to participants:

"The purpose of this workshop is to gather those with strong interests in achieving higher levels of power electronic penetration in our power grid. Power grids of the future will have to withstand increasing stresses caused by elements such as large-scale energy trading, and a growing share of fluctuating energy sources, such as wind and solar power. The grids therefore must become more flexible and better controlled. State-of-the-art and developing power electronics provide a wide range of solutions. Given this, the intent of the Workshop is to discuss some of the most salient technical, economic, regulatory and political challenges; and to roadmap key solutions."

Three technical sessions, at which 12 presentations were given, were titled;

- Applications and Drivers for Increasing Grid PCS
- Advanced High Megawatt PCS Technologies and Approaches
- Technology Development Programs

The presentations were followed by a Discussion session titled:

- Technology Roadmap to Align Expectations

During the Discussion session, the following issues were addressed:

- Applications' Requirements:
- Stakeholders
- System Performance Issues
- Technical Barriers/Issues

Background

The existing US grid has been designed to operate with relatively constant inputs of AC (Alternating Current) power from large electricity generating plants. Power flows are now essentially uncontrolled, following the paths of least resistance through the grid. New issues that challenge the stability and performance of the grid have emerged, including the nearing of end of service life for some of the oldest components, identification of many points of congestion due to overloading of existing lines, and issues associated with intermittent and rapidly fluctuating deliveries of power from solar and wind generators, which have produced stability problems in some instances.

As a result of significant subsidization of "green" power production by solar, wind, and fuel cell technologies including federal and state R&D funding, ITC (Investment Tax Credits), PTC (Production Tax Credits) and RPS (Renewable Portfolio Standards), the amount of electricity generated by these new solar and wind generators has continued to increase. As shown in Table 1, the Reference Case published in the EIA (Energy Information Agency) 2012 Annual Energy Outlook (Tables A18 and A8) predicts further increases in the future.

Table 1. Prediction of Solar and Wind Power Growth

Electricity Production. Billions of kWh	**2010**	**2020**	**2035**
Solar (not including off-grid PV (photovoltaics)	4.48	23.87	43.96
Wind	94.95	154.40	194.23
Total of Solar and Wind	99.43	178.27	238.19
Total US Production	3955	4084	4572
% Solar and Wind of Total US Production	2.51	3.78	5.20

These predicted significant increases in solar and wind power production are dependent in part on both continuing federal and state subsidy programs and the future price of natural gas. With large increases in the rate of natural gas production that has been achieved to date from shale formations and further increases anticipated, the price of natural gas, now about $3/million BTU (British Thermal Units), results in natural gas fueled power being cheaper than non-subsidized solar and wind power.

Current issues with grid instability have been experienced at times of peak wind power availability in Europe, the Bonneville Power Administration system and in Texas, all of which have large wind power facilities. The ability to control power flows within the grid will allow transmission of additional net power flows through the grid by avoiding reaching congestion points on specific lines. The SiC to replace Si (Silicon) in many components of PCS is leading to cost effective performance of newly developed devices in many applications. Power flow control technology based on newly available SiC based components and devices is likely to be less costly than expanding the grid with current technology. Both state-of-the-art and developing power electronics provide a wide range of solutions to current grid issues.

3. Brief Summaries of Presentations

This section of the Proceedings presents brief summaries of each of the Technical presentations. The complete set of presentations can be viewed or downloaded at the NIST High Megawatt Workshop site at http://www.nist.gov/pml/high_megawatt/may-2012_workshop.cfm.

A. Applications and Drivers for Increasing Grid PCS

Wind PCS Architectures

Over the last 33 years, the output and size of typical state of the art wind turbines has increased from 30 kW (kilowatt) with 10 m (meter) rotors in 1979 to 3000 kW with 90 m rotors (175 m high structure) in 2003. The recently announced next step will be a 7000 kW machine with a 164 m rotor. Impediments for wide proliferation of wind assets are the cost of wind generation (capital and maintenance), risks associated with variability of wind (intermittency and unpredictability), barriers for transmission (transportability), and compliance with smart grid infrastructure requirements.

Companies that manufacture wind generators need a long-term business case certainty to support sustained investment. Profitability will be attained only if wind powered LCOE (Least Cost of Electricity) without the benefits of PTC and other subsidies is less than the LCOE of power produced with gas turbines fueled with natural gas.

It appears that HVDC (High Voltage Direct Current) might be the future technology of choice to transport power from wind power plants over long distances (e.g. from deep water offshore to onshore). However, significant challenges are needed in protection and control of such DC architectures.

Other R&D power conversion activities that have the potential to lead to lower wind power costs are:

- Technology to reduce the cost of crossover from low voltage to medium voltage to HVDC
- Utilization of combinations of technologies (e.g. hydraulic transmissions with synchronous generators coupled to the grid).
- DC turbines combined with DC collection has the potential to offer up to 30% improvement in reducing energy losses. This improvement is obtained through reduction of turbine-side and station-side converters. However, the challenge is in realizing such high power DC/DC converters.

(Manjrekar)

Solar Power Integration

Solar Power generating systems have the attributes of no fuel or O&M (Operating and Maintenance) expenses. The cost of capital required for large installations is the major expense. It is typically provided by IOU (Investor Owned Utilities) that put in their rate base, or by public power agencies through bond financing.

The major trends currently in grid modification and upgrading are that new major transmission installations are DC and that Back-to-Back DC links that are inserted in major AC ties. The increasing amounts of widely dispersed small-scale DG (Distributed Generation), which is primarily solar, offers the potential for Reactive Power control and Ancillary Services via PCS, improved system stability, and FIDVR (Resistance to Fault Induced Delayed Voltage Recovery). Advanced communications and control of inverters will enable PV to virtually behave like conventional generation

Given the availability of high power PCS at the transmission level, DG systems can have the same characteristics; DG can/will be centrally controlled, but with highly autonomous functions, and distributed PCS can/will replace capacitors, regulators, etc. This combination can lead to a truly coordinated, inherently stable, self-healing grid.
(Reedy)

Fuel Cell Power Integration

The challenge facing fuel cell power plants over the last thirty years has been that their delivered capital cost has been too high to compete with grid-delivered electricity. However, there have been a large number of sites where superior environmental performance and very high reliability have provided enough value to the owner to justify the relatively high capital cost. In many cases, subsidies from federal and state governments have reduced the owner’s cost to an acceptable level.

Direct FuelCell (DFC)® power plants (300 kW, 1400kW and 2800 kW) manufactured by FuelCell Energy that utilize molten carbonate technology are generating ultra-clean, efficient and reliable power at more than 50 distributed power locations worldwide. Over 180 megawatts of power generation capacity has been installed or is in backlog. Multi-MW sites (4x2800kW) rated at 11.2 MW at Daegu, South Korea, and a 10.4 MW facility at Yulchon, South Korea with a 22.9kV express feeder connection to the sub-station are in operation

From 2003 to 2010, Fuel Cell Energy achieved 70% $/kW cost reduction in their fuel cell power plants through value engineering, power-uprating, and economy of scale.

FuelCell Energy is actively implementing micro-grid mode at several sites including Central Connecticut State University (Gensets and 1.4 MW fuel cell), San Jose Water Treatment Plant (Gensets and1.4 MW fuel cell) Santa Rita County Jail (DOE Smart Grid Demonstration {Facility Static Switch Disconnect, 1 MW early generation Fuel Cell, Gensets,1 MW solar, 2 MW energy storage})

Distribution system limitations have been encountered including the need for Express Feeders for systems larger than 1.5/3.0 MW, voltage regulation, and protection scheme limitations at sub-station minimum loads. Smart grid technologies may reduce technical, jurisdictional, and statutory constraints. In Germany, LVRT (Low Voltage Ride Through) is required for fuel cells connected to the Medium Voltage Network (i.e. Distribution Systems).
(Bernsten)

UTC Power manufactures phosphoric acid fuel cells for stationary power markets and Proton Exchange Membrane (PEM) fuel cells for transportation markets. Their PC50 product for the stationary power market utilizes four Cell Stack Assemblies in series to produce 400 kW at greater than 850V at base load. Forty-two of these units have entered service since 2010. Previous 200 kW products were placed in service in more than 250 installations. Examples of PC50 product installations are Price Chopper (New York), St. Helena Hospital (California), The Octagon (New York), Coca-Cola Enterprises (New York), Samsung/GS Power (South Korea), and the World Trade Center (Freedom Tower, New York).

These units contain 470 kVA (kiloVolt Amperes) inverters which are directly connected to the grid with no isolation transformer. The PCS is ~97% efficient. Fifty percent production cost reduction has been achieved since production of the first seven units in 2011. Another 30% cost reduction is needed to reach their cost goals

Their PC40 product for transportation markets produces 120 kW from PEM stacks. Eighteen quiet, zero-emission fuel cell buses are currently in service in the United States. The PCS system utilizes a modular inductor, dc-dc converter and inverter modules. A 25% cost reduction was achieved relative to the first seven units produced in 2010. An up-rated 150 kW PC58 product for these markets is now in the conceptual design phase. The goal is a 60% cost reduction resulting from the increased power rating and improved integration with external systems.
(Singh)

Grid Storage Integration

Grid-tied energy storage mediums are predominately DC in nature. To effectively utilize the energy storage capacity on the present electric utility grid, the energy must be converted to a standard AC level and regulated through a converter. Converters used for this purpose must achieve bi-directional conversion from AC to DC and DC to AC, AC grid to DC storage isolation and protection, interconnection and control of multiple DC sources, and regulated, stable and controllable power flow.

Basic inverter operation includes sinusoidal pulse width modulation and phase locked to grid, reference signal provided to compare with triangle waveform, gates are triggered as output of controller modulation is provided to control power, and output is filtered to provide limited harmonics/switching noise.

Basic AC/DC power conversion topologies include both Single Stage Converters and Multi-Stage Converters. Single Stage Converters are limited to DC voltages > 1.5X VACRMS (Volts AC Root Mean Square) and designed to achieve maximum efficiency. Multi-Stage Converters are characterized by maximum DC voltage range, increased losses, and increased hardware cost. Advanced power conversion topologies include multi-port/multi-stage converter, Z-inverter, and multi-level inverters.

The key conclusions from this presentation are:

- Power conversion is an integral part of ESS (Energy Storage Systems)
- Limit conversion stages are used to maximize efficiency and minimize complexity
- Integrate systems as soon as practicable to avoid grid interaction and maximize efficiency
- Modularized systems offer unique advantages in redundancy and expandability
- Advanced and hybrid topologies may offer the best solution for specific ESS challenges.

(Clark)

B. Advanced High Megawatt PCS Technologies and Approaches

PCS Connected Microgrids:

Pareto Energy offers a packaged unit to safely connect microgrids to utility grids by means of a parallel non-synchronous interconnection. The package is similar in size to a shipping container, requiring a pad with a length of about 50 feet. The packaged unit is designed for drop-in installation with no on-site fabrication.

The contents of the package includes active rectifiers, packaged output inverters, switchgear and a 4 MVA transformer. Functionally, it has been designed to eliminate the potential of voltage, frequency, and phase-angle mismatching between the facilities and the utility grid and preclude any potential detrimental effects on the utility power delivery system.

(Flank)

Advanced HMW Converters

Electrical grids come in many sizes. Among the largest are the regional US power grids. Microgrids exist in neighborhoods and commercial sites. Homes can be considered as nano-grids, while the combination of an auto and recharger can represent a pico-grid. Most electricity is consumed by electronic loads, which are constant-power loads. In the future, more electricity may be supplied by DC electronic sources such as renewables, batteries, and pumped storage, as these systems increase in size.

The CPES (Center for Power Electronics Systems) at Virginia Tech has set up a home DC nano-grid experiment. It has a bus architecture with two voltages, wireless communication, bidirectional power conversion, separation of dynamics, integrated protection, load management, DG management, data acquisition, communication, and islanded operation.

In addition, CPES is experimenting with a 10 kW, 20 kHz Prototype single-phase nano-Energy Control Center with bi-directional topology, bi-directional control system, bi-directional current limit, bi-directional EMI compatibility, and low dc leakage current, all with low cost and high density.

Many system configurations are possible for multi-level converters for high-voltage applications including Neutral Point Clamped, Diode Clamped, Active Clamped, Flying Capacitor, Cascaded, Cascaded H-Bridge, Asymmetric Cascaded H-Bridge, and Modular Multilevel

Research is recommended in the areas of Network Architectures and Control, High-Power and High Power-Density Converters, and Safety and Reliability to replace electric energy “railways” with “highways”. Education is recommended to instigate an innovative intellectual “Ecosystem” in the areas of Network Architectures, Energy Transfer Protocols and Markets, High-Power and High Power-Density Converters, and Safety and Reliability.
(Boroyevich)

SiC Power Devices/Materials:

The commercial availability of high quality (low defect concentration) SiC in steadily increasing size wafers at steadily lower prices has allowed the commercial development of multiple high performance devices which have markedly improved performance relative to Si-based devices. The significant properties of SiC relative to PCS are:

- 10X Breakdown Field of Si
  - Allows lower specific on-resistance and faster switching for the same breakdown voltage
- 3X Thermal Conductivity of Si
  - Allows higher current densities
- 3X Bandgap of Si
  - Allows higher temperature operation

Currently available SiC-based products from Cree Inc. include 1-20A 600V Z-Rec SiC JBS diodes, 4-20A 650V Z-Rec SiC JBS diodes, 2-40A Z-Rec 1200V SiC JBS diodes, 5-50A 1200V SiC JBS diodes, 10 and 25A 1700V Z-Rec SiC JBS diodes, and new

1200V/50A & 1700V/50A SiC JBS diodes and MOSFETs which are scheduled to be released in the Fall of 2012.

Cree Inc. shipped 113 GVA (Giga Volt Amps) of SiC related products in 2011. Since 2005, cost reductions of over 5x have been achieved as a result of higher quality SiC material, larger production volumes, and an increase in SiC wafer size from 3 inch to 100 mm. The Field Failure Rate since January 2004 has been 10 times lower than the typical silicon

Since the mid 2000's several high voltage (>10 kV) SiC devices have been developed and demonstrated in power converters; for example 10 kV SiC MOSFETs have been demonstrated in Megawatt scale power converters switching at >20 kHz. Highlights of the SiC IGBT (Insulated Gate Bipolar Transistor) recently developed under the ARPA-E ADEPT (Agile Delivery of Electrical Power Technology) Program include:

- Development of 15 kV SiC IGBT – World's highest voltage semiconductor switch
    - Over 2x higher than 6.5 kV SiC IGBT
- SiC IGBTs are capable of switching over 20x faster than Si IGBTs
- Higher voltage and switching speed of SiC IGBTs enables a 3x to 5x reduction in the size and weight of a Solid State Transformer
- SiC IGBTs result in a 3x to 4x reduction in losses for that Solid State Transformer

(Grider)

Silicon Carbide Device Update

The advantages of SiC relative to other power semiconductor materials include

- Most mature "wide bandgap" power semiconductor material
- Electrical breakdown strength ~ 10x higher than Si
- Commercial substrates available since 1991 –
    - now at 100 mm diameter, 150 mm diameter soon
- Defects up to 1,000 times less than GaN (Gallium Nitride)
- Thermal conductivity ~ 3x greater than Si or GaN

Important applications for SiC-based devices are:

- Low voltage-PFC/Power supplies
- Medium voltage-PV inverters, motor controllers, hybrid automotive
- High Power – ships and vessels, smart power grid, windmills, rail transport

SemiSouth Laboratories offers 1200 V – 1700 V Trench "normally – off" JFETs, 650 1200V-1700V Trench "normally – on" JFETs, and 1200 V Schottky diodes. SiC Trench JFET offers lower cost, 3-10x smaller die size and up to 50% fewer manufacturing steps. Performance attributes include 5-10x lower switching energies, normally-on or -off, which enables both high-frequency and high-efficiency operation.

Using SemiSouth Laboratories SiC JFET, Future Power Electronics Technology developed an all-SiC-device-based three-phase inverter with a 500 cc volume, verified to achieve an output power density of 30kWh/l, which is believed to be the highest achieved to date. The power modules in the device operate at up to 200°C. At 15 kW output, the conversion efficiency of this 500 cc device was 99%.
(Sheridan)

C. Technology Development Programs

Army Programs

Power loads continue to rise on all military platforms. Mission capability on both current and future platforms is driven by effective use of electric power. SiC-based converters provide greater power density and finer control than Si-based converters. However, their maturity/reliability and cost is still considered a risk factor by Army Program Managers. There is a major focus on increased efficiency and temperature for size reduction and fuel economy.

Soldier requirements are for a 72 hour mission using high energy batteries, hybrid power sources, and photovoltaic technologies in sizes of microwatts to 10s of watts. Requirements for mobile systems include Silent Power using Fuel Cell auxiliary power systems, Reforming, and Power MEMS (micro electromechanical systems) technologies in air or ground domains in sizes 100s of watts to 100s of kW. Platform technologies on the ground require high power switching and conditioning, intelligent power management, and integrated thermal management in sizes up to 1000s of MW.

The Army anticipates multiple benefits accruing from the use of SiC power electronics including reduced SWAP (system Size Weight And Power), reduced cooling requirements, increased efficiency at high voltage, and higher operating temperatures. Overall, these will be easier to integrate onto military ground vehicles than silicon based systems and provide significant improvements in mobility performance and fuel economy. Requiring SiC high-frequency operation (in the future at high-temperature) will push the limits of the devices as well as the packaging technology and passive components.

Pulse Power electronic survivability architecture is being developed to support hybrid armor, external power distribution (uncooled), and a store of local high power energy without the engine operating. The challenges include the needs for high temperature, high frequency, high current, low loss switching, high temperature advanced magnetics, high temperature/density storage and conversion capacitors, high voltage “power brick” battery, ultra-fast high-voltage GW switches and cooling through conduction only.

The SiC ManTech program (FY(Fiscal Year) 2004-2009; under ARRA (American Recovery and Reinvestment Act of 2009) since FY2011) has focused on development of SiC power MOSFET and diode development to replace Si power electronics. Future plans for this program include development of GEN(Generation)-1 (ManTech) 1.2 kV / 80 A SiC MOSFETs and Schottky diodes, GEN-1 (ARA) 1.2 kV / > 100 A SiC MOSFETs and GEN-2 1.2 kV / >200 A SiC MOSFETs (WEG (Worldwide Equipment Guide)>100°C).

Future plans for SiC power switch development for continuous power applications include a SiC TDS (Traction Drive Systems) module operating at 80°C and 100°C WEG, with 70% greater efficiency than Si TDS module and at 40% replacement, and to mature MOSFET to 300 A @ > 100°C WEG.

Planned developments focused on Pulse Power applications include Si SGTO (Super Gate Turnoff Thyristor) die pulse switch operating at 10x power density of Si whole-wafer switch, SiC SGTO die operating at 2x greater power density than Si SGTO die and programs to mature SiC switch power density by another 2-3x at increased efficiency.

This component work can reduce power system size by up to 2x for continuous and 4x for pulse power applications with efficiencies at >2x compared to Si-based systems. **(Scozzie)**

Navy Programs

The SSPS (Solid-State Power Substation) is part of the DARPA High Power Electronics (HPE) program. The objective is to develop compact, light-weight power converters and transformers for the US Navy that are enabled through high voltage switches. A single-phase SSPS has undergone testing at the Navy test lab with the following results:

- Demonstrated at 1 MVA, 13.8 kV/265 V
- Based on 10 kV, 120 A, 20 kHz SiC MOSFET/JBS-diode Modules
- Efficiency at full load > 97%
- 1/3 weight of conventional transformer
- Clean 20 kHz waveforms
- Balanced sharing of voltages/currents
- AC input current output voltage THD (Total Harmonic Distortion) < 5%
- Cooling of HF transformers and busbar/connections is challenging

A 1 MW, 4160Vac – 1000Vdc supply prototype is now under assembly for AMDR (Air and Missile Defense Radar) service and is scheduled for TRL6 (Technical Readiness Level 6) testing in the fourth quarter of 2012. It is also based on the 10 kV, 120 A, 20 kHz SiC MOSFET/JBS-diode Modules and has 1/3 the volume and 1/10 the weight of the existing supply.

Potential industrial applications for this type of unit include
- Renewables
    - Enable power conversion and grid interface at higher voltage to reduce complexity and cost

- Rail
    - More efficient locomotive drives - reduce switching/diode recovery losses
    - Compact transformers/electronics for catenary interface
- T&D
    - Reduce number of series devices needed to handle high voltage
    - HVDC/ FACTS (Flexible AC Transmission) converters with lower component count/complexity
    - Compact solid-state distribution transformers
    - (smaller footprint, added functionality, oil-free)

Challenges for high voltage SiC material in this application include:

- Cost – need market volume and higher yields
- Reliability - need validation from early adopters
- Limited current ratings for present devices/ modules
    - T&D (Transmission and Distribution), Drives, Wind applications will require higher ratings
    - Need large-area chips with good yields
- Development of supporting HV (High Voltage) components – passives, gate drives, packaging, insulation
- For HV applications, they need to be cost-competitive compared with multilevel converters with LV (Low Voltage) silicon

(Beermann-Curtin)

ARPA Programs

The major ARPA-E missions are to enhance the economic and energy security of the US and to ensure that the US maintains the technological lead in developing and deploying advanced energy technologies. The strategies are to find and fund high-risk, high-impact projects, invest in the best ideas and teams, tolerate and manage high technical risk; accelerate translation from science to markets, and fund both proof of concept and prototyping.

ARPA-E has a number of technology development programs under way including GENI (Green Energy Network Integration) to make the existing grid stronger and more reliable, have the flexibility to dispatch power in real time, and to enable 10x more renewable energy to flow through the grid to power customers. Both hardware and software development are supported.

GENI architectures for the grid are focused on routing electrical power and mobilizing large numbers (100k) of small assets. Topology Control Algorithms are being developed to optimize the performance of individual transmission lines. Projects utilizing multi-party teams are involved in the development of HV grid-scale transistors, Solid-State Transformers (SST), power routers to augment existing transformers, utility-scale inverters, distributed inverters, and micro-inverters.

Specific project examples from ARPA-e GENI, ADEPT, and Solar-ADEPT programs include:

- Development by Cree of a 15 kV/20 A SiC p-IGBT -- the world's highest voltage semiconductor switch
- Scalable real-time decentralized Volt/VAR (Volt Ampere Reactive) control. Key innovations include distributed control through local sensing, computation, and communication, yet jointly optimize certain global objectives and characterization of AC-OPF sub-problems that are polynomial-time solvable
- Open ADR (Automatic Demand Response), low-cost, internet-protocol based telemetry solutions, and intelligent forecasting and optimization techniques to provide "personalized" dynamic price signals to millions of customers in timeframes suitable for providing ancillary services to the grid
- Utility scale 1 MW Photovoltaic Inverter to cost an estimated \$0.2/W
  (in China \$0.17/W)

(Gradzki)

4. Discussion - Technology Roadmap to Align Expectations

Application Requirements

Different organizations have different but very specific requirements related to the specific operations that they are planning to carry out. For example the Army and Navy often have very strict performance goals for specific equipment items. These items are subject to weight, space, fuel consumption, electrical efficiency and other constraints not required in conventional, non-defense applications. Electrical efficiency is very important when producing electricity either on-board or on-site fueled from an off-site location. These different constraints establish different values that the customer is willing to pay for the component, device or system. There are limited markets for high-priced, low value production items. If the market doesn’t expand it is difficult to reduce the price of an item.

Stakeholders

The 32 Workshop participants represented a very broad group of interests. The most heavily represented group was the equipment vendors (13), followed by federal agencies (7) (including ARPA-E (3) DOE (2), ORNL (Oak Ridge National Laboratory) (1) and NIST (1), DOD (3)), universities (4), state agencies (2) consultants (2), and ISO (Independent System Operator) (1). At this workshop, we were not able to benefit from the participation of power producers, either IPP or utility, that have to deliver their product to market via T&D systems. Several organizations including ARPA-E are funding R&D to increase the efficiency of and reduce the cost of transmission.

System Performance Issues

One of the overriding issues at both the state and federal levels is the avoidance of wide-area blackouts, which often result in actions taken automatically to protect the grid from instability. It has been suggested that relaxing some of the frequency regulation standards by a small amount, could result in a major reduction in the probability of an area-wide black-out due to automatic control actions.

One of the major difficulties in reducing the cost of PCS products is the fact that the core inverter technology represents only about 30% of the total cost of that product. Reducing only cost of the core inverter technology, without major reductions in the other components in the product can only result in a small reduction in overall cost.

The ARPA-E cost goal for PV inverters is 10¢/W. Is that low enough for PV solar and other applications? Can it be achieved?

Technical Barriers/Issues

In order to gain the confidence of potential customers, very extensive field testing of components, devices, and systems is required to demonstrate that they will perform as specified under the conditions specified, for the lifetime specified with the reliability specified. Both prototypes and full-scale items must be tested extensively to meet these requirements

A number of Army, Navy and ARPA-E test programs that are briefly noted below were described at the Workshop.

- The Navy is successfully testing a single-phase SSPS, with 1/3 the weight of conventional transformer at 1 MVA, 13.8 kV/265 V with > 97% efficiency at full load. Further testing of a 1 MW, 4160Vac – 1000Vdc supply prototype with 1/3 the volume and 1/10 the weight of the existing supply is scheduled for TRL6 (Technical Readiness Level 6) testing in fourth quarter of 2012.

- The Army is developing a variety of components that have evolved from earlier lower power components, including 1.2 kV / 80 A SiC MOSFETs and Schottky diodes, 1.2 kV / >100 A SiC MOSFETs , 1.2 kV / >200 A SiC MOSFETs (WEG >100°C).

- Southern Company is testing Power Flow Controllers which augment existing transformers developed by a team consisting of Waukesha, Varentec, Georgia Tech. and EPRI (Electric Power Research Institute) with ARPA-E funding. 13 kV/1MW units are being evaluated in a tie-line field demo and a 13 kV, 5 bus test bed is in operation to show routing.

- A multistage PV inverter that utilizes high-voltage switches and a high-frequency transformer has been developed by Ideal Power Converters. It has 1/10 the weight, 1/3 lower losses and 1/2 the manufacturing costs of comparable units in service today**.**

4. Conclusions

The major conclusions that can be drawn from the presentations and discussions at this Workshop are that:

The existing electrical grid needs replacement of aging components, expansion of capacity to accommodate increased population and increased per capita use of electricity, utilization of advanced PCS to improve transmission efficiencies, initiation of some control of power flows, and development of capability to better cope with the issues resulting from the delivery of increased penetration levels of intermittent and rapidly fluctuating power from solar and wind generators.

The growing availability of high quality SiC material and SiC–based components and devices has enhanced the capabilities of PCS components such as Schottky diodes, JBS (Junction Barrier Schottky) diodes, JFETs (Junction Field-Effect Transistors), MOSFETs (Metal-Oxide Semiconductor Field-Effect Transistor), and IGBTs. Many of these items have capabilities that cannot be achieved with Si-based components. The number, capability, and commercial availability of these products is increasing rapidly at this time and can play a significant role in upgrading the US electrical grid.

This commercial availability of SiC-based components is attributable in large part to the long-term funding of R&D (Research and Development) programs that has been provided by numerous agencies of the Department of Defense (DOD) as well as by other federal agencies including NIST and ARPA-E (Advanced Research Projects Agency-Energy). Much of this R&D has been done by integrated teams that have included private sector companies, national laboratories, and universities.

Additional research and development is needed to improve PCS systems to meet specific DOD operational requirements and ARPA-E goals of ensuring the economic and energy security of the US (United States) and to ensure that the US maintains the technological lead in developing and deploying advanced energy technologies.

6. Appendices

A. Final Workshop Agenda

High Megawatt Power Conditioning System Workshop

Technology Roadmap
for Increased Power Electronic Grid Applications and Devices

NIST

Gaithersburg Maryland

8:30 am to 5 pm, May 24, 2012

Workshop Objectives

The purpose of this workshop is to gather those with strong interests in achieving higher levels of power electronic penetration in our power grid. Power grids of the future will have to withstand increasing stresses caused by elements such as large-scale energy trading, and a growing share of fluctuating energy sources, such as wind and solar power. The grids therefore must become more flexible and better controlled. State-of-the-art, and developing power electronics provide a wide range of solutions. Given this, the intent of the Workshop is to discuss some of the most salient technical, economic, regulatory and political challenges; and to roadmap key solutions.

Agenda

8:00am Breakfast

8:30am Introductions and Objectives Al Hefner/Leo Casey/Ron Wolk

8:45am Applications and Drivers for Increasing Grid PCS

Wind PCS Architectures:	Madhav Manjrekar	(Vestas)
Solar Grid Integration:	Bob Reedy	(Florida Solar Energy Center)
Grid Storage Integration:	Kyle Clark	(Dynapower Company)
Fuel Cell Integration:	George Berntsen	(FuelCell Energy)
	TJ Singh	(UTC Power)

10:15am Break

10:35am Advanced HMW PCS Technologies and Approaches

PCS Connected Microgrids:	Shalom Flank	(Pareto Energy)
Advanced HMW converters:	Dushan Boroyevich	(Virginia Tech)

SiC Power Devices/Materials:	Dave Grider	(Cree Inc.)
SiC Power Devices	David Sheridan	(SemiSouth)

12:00noon Lunch

1:00pm Technology Development Programs

Army programs:	Skip Scozzie	(Army Research)
Navy programs:	Sharon Beermann-Curtin	(Office of Naval Research)
ARPA-e programs:	Pawel Gradzki	(Booz Allen Hamilton)

2:00pm Technology Roadmap to Align Expectations

Discussion Leader:	Leo Casey	(Satcon)

Applications Requirements:

Control of voltage, power-factor and faults through solid-state devices. Integration and control of renewables and storage. Seamless isolation from grid outages and disturbances through microgrids. Ability to relieve congestion. Achieve improved demand and supply response.

Stakeholders

Power producers, ISOs, grid operators, utilities, power electronic equipment manufacturers, energy and power generation/storage manufacturers. (related stakeholders also include regulators, safety/standards bodies, rate payers, investors)

System Performance Issues

a. Cost, efficiency, reliability, overload, fault behavior
b. Advantages and possibilities

Technical barriers/issues

a. Controls, communications, anti-islanding, lvrt, optimization (device, site, system,…)
b. C&P

Hardware Issues –

a. What are the gaps in terms of devices, systems, integration,

Technology Demonstration Issues

a. Technologies, scale, number

5:00pm Adjourn

B. List of Workshop Attendees

Name	Affiliation	Email Address
Beermann-Curtin, Sharon	Office of Naval Research	Sharon.Beermanncurti@Navy.Mil
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C. List of Workshop Presentations

Beermann-Curtin
Next Generation Technologies for Today's Warfighter
Sharon Beermann-Curtin –Office of Naval Research

Berntsen
Fuel Cell Applications for Power Electronics
George Berntsen, Fuel Cell Energy

Boroyevich
Advanced High-Megawatt Converters for New Grid Architectures
Dushan Boroyevich, Center for Power Electronic Systems, Virginia Tech

Flank
PCS Connected Microgrids
Shalom Flank, Pareto Technologies, Inc.

Gradzki
ARPA-E Stimulating Energy Innovation
Rajeev Ram, Program Director, ARPA-E and Pawel Gradzki, Booz Allen Hamilton

Grider
Advanced SiC Power Technology for High Megawatt Power Conditioning
David Grider, Anant Agarwal, Sei-Hyung Ryu, Lin Cheng, Craig Capell, Charlotte Jonas, Al Burk, Michael O'Loughlin, Mrinal Das, and John Palmour; Cree, Inc.

Manjrekar
Wind – challenges, opportunities, and PCS
Madhav D. Manjrekar, Vestas

Reedy
Driven by the Sun --"Powerful" Thoughts on PCS Development
Bob Reedy, Florida Solar Energy Center

Scozzie
Status of SiC Power Devices for Compact High-Efficiency High-Temperature Power Circuits
C. J. Scozzie, U. S. Army Research Laboratory

Sheridan
Silicon Carbide Device Update
David Sheridan, Semi South Laboratories

Singh
Fuel Cell Power Electronics – Status & Challenges
Tejinder Singh, UTC Power