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Table of Contents

Section	Title	Page
1	Summary	1
2	Introduction	3
3	Markets for High Megawatt Power Converters	4
	A. Current Markets	4
	B. Future Commercial Markets	5
	C. Future DOD Markets	6
4	Integration of Workshop Presentation Information	8
	A. New Approaches to System Design	8
	B. New Topologies	9
	C. New Materials	12
	D. New Components	14
	i. Inverters	14
	ii. Transformers	16
	iii. Capacitors	17
	iv. Integrated Devices	18
5.	Grid Connection Issues	19
6.	IGFC Systems	20
7	NIST/DOE Project for Evaluation of PCS Options for IGFC Power Plants	22
8	Formation of Roadmap Committee	25
9	List of Workshop Presentations	27
10	Appendices	29
	A. Workshop Agenda	29
	B. List of Workshop Participants	30
	C. Workshop Invitation Letter	32

List of Abbreviations

AC	Alternating Current
ARL	Army Research Laboratory
BJT	Bipolar Junction Transistor
ERDC-CERL	US Army Engineer Research and Development Center, Construction Engineering Research Lab
DC	Direct Current
DIMOSFET	Dielectric Metal-Oxide-Semiconductor Field Effect Transistor
DOD	Department of Defense
DOE	Department of Energy
EMALS	Electromagnetic Aircraft Launch System
EMI	Electromagnetic Interference
EPRI	Electric Power Research Institute
FACTS	Flexible AC Transmission System
FC	Fuel Cell
FCE	Fuel Cell Energy
GTO	Gate Turnoff Thyristor
GW	GigaWatt
HF	High Frequency
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistor
IGCC	Integrated Coal Gasification Combined Cycle
IGCT	Integrated Gate Commutated Thyristor
IGFC	Integrated Coal Gasification Fuel Cell
IPS	Integrated Power System
JBS	Junction Barrier Schottky
JFET	Junction-Field Effect transistor
kHz	kiloHertz
kV	kiloVolt
kVA	kiloVolt Ampere
kW	kiloWatt
LC	Inductor-capacitor
LV	Low Voltage
MJ	MegaJoule
MOSFET	Metal-Oxide-Semiconductor Field Effect Transistor
MV	Medium Voltage
MVA	MegaVolt Ampere
MW	MegaWatt
NIST	National Institute of Standards and Technology
ORNL	Oak Ridge National Laboratory
OSD	Office of the Secretary of Defense
PCS	Power Conditioning System
PEBB	Power Electronic Building Blocks
PEEK	Polyetheretherketone
PEKK	Polyetherketoneketone

PWM	Pulse Width Modulation
R&D	Research and Development
SECA	Solid State Energy Conversion Alliance
SOFC	Solid Oxide Fuel Cell
UMOSFET	U-Shaped Metal-Oxide Semiconductor Field Effect Transistor

1. Summary

On January 24, 2007, a group of forty-two Power Conditioning Systems (PCS) experts invited by the National Institute of Standards and Technology (NIST), the Department of Energy (DOE) Office of Clean Energy Systems, and the ERDC-CERL assembled at a High Megawatt Converter Workshop held at NIST headquarters in Gaithersburg, Maryland. An Organizing Committee consisting of Dr. Samuel Biondo (DOE), Dr. Allen Hefner (NIST) and Frank Holcomb (ERDC-CERL) recommended the invited participants and presenters. The objectives of the Workshop were to exchange information focused on state-of-the-art technologies for High Megawatt Converter systems, discuss the merits of proposed approaches to achieving significant cost reduction and improved DC to AC 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.

Markets

There are significant opportunities for more widespread use of advanced PCS systems in current markets, future commercial markets, and future DOD markets.

Promising Areas for Improvement of PCS Cost and Performance

The various options presented at the Workshop for achievement of improved performance and reduced cost PCS were:

- Physics based simulation and design systems
- Advanced Topologies
- Advanced materials (i.e., SiC)
- Standardized components (i.e., PEBB)
- Intelligent integrated modules
- Improved components based on advanced technologies (i.e., nanocrystalline transformers, high temperature polymer capacitors)
- Relaxation of utility grid connection standards

Each of these areas appears to have significant potential for improving overall system performance.

NIST/DOE Evaluation of PCS Options for IGFC Power Plants

DOE and NIST have entered into an Interagency Agreement to evaluate various options to convert low voltage power produced in fuel cells in central station scale plants to the very much higher power levels required for delivery to the grid. Various conversion approaches that focus on the use of advanced technologies for low-voltage, medium-voltage, and high-power PCS approaches will be evaluated to determine areas requiring substantial federal government investment to meet the cost and efficiency goals of the SECA FutureGen Power Plant.

Roadmap

The Workshop participants agreed that an industry-led Roadmap process needed to be initiated to offer guidance for further development of PCS that could meet the requirements for more cost effective and more efficient power conversion. A number of attendees expressed a willingness to serve on such a committee and, in addition, the names of other potential committee members were proposed. Also, there were positive suggestions made that a federal interagency task group for high-megawatt power converter technologies could play an important role in this area.

2. Introduction

Power Conditioning Systems (PCS) are ubiquitous throughout modern society. They are used in systems that collect electricity from a variety of AC and DC generating sources, transmit either AC or DC electricity, and deliver the desired quality of AC and DC electricity required for use in motors, drives, lighting systems, computers, etc. Their continued development is evidenced by ever larger system capacity, lower cost, increased reliability, and higher efficiency.

Further development is required to achieve additional capabilities to support the commercialization of new technologies for higher efficiency power production, higher efficiency utilization of electricity, and to support industrial, commercial, residential, and defense applications.

There is a broad community of interest that can benefit from continued development of PCS technology. The federal government typically has provided R&D funding for pre-commercial R&D that has the potential for large and long-term public benefits. One of the current focuses of the U.S. Department of Energy R&D program for future power generation systems is the development of technology to support the future commercialization, beginning in 2020, of a very high efficiency, 100-800 MW central station, Integrated Coal Gasification Fuel Cell (IGFC) power plants. DOE has established a total cost goal for the Power Island in such plants of $400/kW. That total goal is inclusive of individual component cost goals for the SOFC fuel cell stacks and PCS in the Power Island ($100/kW and $40-100/kW, respectively).

It is envisioned that the fuel cell building block used in the Power Island in an IGFC power plant will be low cost, mass produced, Solid Oxide Fuel Cell (SOFC) stacks based on technology currently being developed under the Solid State Energy Conversion Alliance (SECA) program. These stacks would be specifically designed to convert coal-derived fuel gas to electricity. That program is targeting the completion of the research in 2012 that would support production of the SOFC stacks in the Power Island at a cost of $100/kW.

Current PCS systems that are used in natural gas fueled, fuel cell, distributed generation power plants, with outputs of 100 kW to 1.2 MW, are estimated to cost $260/kW at best and perhaps more depending on the specific application. Achievement of the DOE cost goal for the PCS of $40-100/kW will require that a great deal of progress be achieved in the areas of system topology, materials, device design, and new approaches to connections to the AC electrical grid to reduce PCS costs from current levels to DOE targets. This goal is acknowledged within the PCS industry as a difficult stretch goal.

3. Markets For High Megawatt Power Converters

A. Current Markets

The array of markets that currently utilize high megawatt power electronics is quite broad and includes the following applications:

Generation – Wind farms, Fuel cells, Variable speed hydro
Storage - Battery, Flywheel, Super Capacitor, Superconducting Magnet
Transmission – HVDC (High Voltage DC), FACTS (Flexible AC Transmission System)
Distribution – Customer power
Industrial – Variable speed drives, Rail transportation, Ships
Military – Ship Power, Aircraft launch, Weapons, Base power
(Hingorani Slide 2)

Specific examples of several of these applications include:

- >1 GW Level Pacific Intertie HVDC System
  - DC Link Voltage: ±500kV
  - Power Level: 3100 MW
  - Circuit Topology: Current Source Inverters
  - Device: 6.5kV Thyristors stacked up for 133kV blocking
  - Switching Frequency: 60Hz
  - Problems: >5 acres of land for LC filters
- >100 MW converters for reactive power compensation
  - Circuit Topology: multiple pulse (48-pulse) with transformer isolation
  - Device: 6.5kV GTO
  - Switching Frequency: <500Hz
- >1 MW Distributed Generation
  - 1.5 MW to 5 MW wind power generation
  - 1 MW to 2.4 MW fuel cell power plants
  - IGBT based with switching frequency >5kHz

(Lai Slide 4)

HVDC transmission lines can now be designed for operation at 800 kV DC. This new capability allows higher efficiency and reduced right-of-way requirements. These IGBT (Insulated Gate Bipolar Thyristor)-controlled HVDC systems are now capable of transmitting up to 6000 MW (Tang Slide 25).

PCS technology continues to evolve in terms of lower cost, higher efficiency, and more reliable components. Newer applications continue to evolve as newer materials and integrated devices become commercially available. An example of this progress is the use of silicon carbide components, of ever increasing capability, integrated into newer devices that can support more demanding applications.

"The availability of SiC unipolar/bipolar power devices can enable high-frequency operation for high-voltage and high-power applications leading to new PCS topologies, which offer choices radically different than provided by Silicon-based IGCT (or IGBT). Further, the ability to withstand higher voltage without compromising switching and conduction losses and thermal sustenance can lead to simpler topological structures." (Mazumder Slide 2, presentation not provided)

Among the improved capabilities noted during the Workshop presentations were the commercial use of IGCT and the integration of multiple capabilities into Power Semiconductor Modules.

"The ACS 1000 is the first drive to use a new power semiconductor switching device called IGCT (Integrated Gate Commutated Thyristor). IGCT brings together a versatile new power handling device, the GCT, (Gate Commutated Thyristor) and the device control circuitry in an integrated package." (Enjeti Slide 11)

Commercial installations of MV IGCT Target PEBB (Power Electronic Building Blocks)-based PCS -9MVA IGCT

- 22 MVA Dynamic Voltage Restorer
- 18 MVA Frequency Changer
- 15 MVA Regenerative Fuel Cell
- 60 MVA (40 MW) Battery Energy Storage System

(Hingorani Slide 17)

Intelligent Power Modules that integrate gate drives and protection features in the module package are now being offered. Further integration of system components within a module package are anticipated along with integrating chip cooling in the module. (Leslie Slide 2)

B. Future Commercial Markets

Power conditioning system technology advances in the areas listed below are needed to provide the technology base for a future, cost-effective, and reliable national power delivery system capable of the following attributes:

- Smart power delivery system
- Advanced distribution automation
- Fast simulation and modeling
- Integration distributed energy resources
- Distributed storage technologies
- Improved power system operation and control
- Reduced vulnerability to natural disaster and attack
- Improved power quality (Holcomb Slide 9)

Fuel cells are an evolving technology providing a solution to the need for distributed, high value, on-site power. The current high cost of small (e.g. 250 kW modules combined in units of up to 2 MW) packaged power plants which is in the range of $3500-5000/kW has precluded wider scale applications. The typical cost of the PCS components of those systems is about 10% of the total.

DOE is in the second phase of a three phase Solid State Energy Conversion Alliance (SECA) program to develop much lower cost, natural gas fueled, packaged fuel cell power plant systems based on Solid Oxide Fuel Cell technology. The goal of that effort is to develop the technology to support mass-production of these units at a cost of $400/kW. The cost goal for the PCS part of that system is $40/kW. DOE has initiated another program to use those same types of fuel cells in large, 100-800 MW Integrated Gasification Fuel Cell central station power plants, with the same cost goal for the power island in that plant.

There are a number of fuel cell characteristics that impact the PCS

- Fuel cells respond slowly to changing loads
- Auxiliary power is needed for start-up and to power control systems
- Fuel cell stacks operate at a total voltage of less than 350V. It is possible to increase the voltage output of a pair of stacks by connecting them in series with a center tap to ground. However, it will be necessary to use the PCS to increase the stack output voltage from the cell level (<1 kV) to grid level (18kV).

A number of potential approaches to resolving these issues include:

- Modular topology
- Efficiency improvements with advanced materials (i.e., SiC) and advanced technology (i.e., IGCT)
- Soft switching and high frequency (Jones Slides 2-9)

Heretofore, the PCS systems used in small distributed power plants have focused on delivering power to the local load and interconnecting with the grid to allow both grid-independent and grid-parallel operation. Delivery of power to the grid for transmission to remote load centers will likely result in different problems that must be addressed with different PCS approaches.

C. Future DOD Markets

The DOD is moving in strategic directions that will include the use of much more electric power to support individual soldiers, various kinds of bases, vehicles and ships. Much of this power will be DC. The selected PCS must adapt to these needs.

A section of the 2005 Energy Policy Act directs the DOE to fund selected demonstration projects that involve using hydrogen and related products at existing facilities or installations, such as existing office buildings, military bases, vehicle fleet centers, transit bus authorities, or units of the National Park System (Holcomb Slide 7). Much of the forward deployments of Army personnel in:

- Base Camps
- Life Support Areas
- Advanced Operations Base
- Forward Operations Base
- Tactical Operations Center

require DC power to support their operations. (Holcomb Slide 13)

The DOD has several developments under way that require large amounts of electricity over short durations. These include the Electromagnetic Aircraft Launch System (EMALS) and rail gun. The EMALS, which will be used to replace steam powered aircraft launchers on aircraft carriers, requires 150 MW for 2-3 seconds. The system includes flywheel energy storage and IGBT inverters.
(Staines I Slides 2 and 3)

Another application involves ship mounted rail guns that are used for the rapid firing of projectiles. The requirements for this system include:

- Current source to charge 200 MJ caps to 11 kV
- Max 10 shots per minute → 35 MJ/s average
- Require high power density (> 2 MW/m^3) to fit in available shipboard volume (Staines I Slides 9 and 10)

The development of an integrated power system (IPS) electric ship is also under way:

- The first surface combatant using IPS is DDG 1000 with two propulsion motors rated at 37 MW and ship service loads > 12 MW
- This is a major first step for IPS, but what are the next steps to meet the future IPS needs?
- Spiral insertion of new mission systems such as pulse energy weapons will increase the electric load demands even further (Staines I Slide 6).

4. Integration of Workshop Presentation Information

A. New Approaches to System Design

It was suggested that the current approach to designing systems for DOD, which is now Rule-based, will evolve into a system that is relational-based and has Physics-based analysis at its core.

Today	**Tomorrow**
• Rule Based Design	• Relational Based Design
• Standard Parts	• Standard Processes
• Increasing Complexity	• Increasing Detail
• Specifications, Documents	• Model is the Specification
• Small Samples Statistics	• Physics Based Analysis
	• Statistics from All of Industry

(Ericsen Slide 2)

This evolution will mean that simulation, which is now used for analysis but requires detailed design information, will evolve to a situation where simulation will become part of the design process and *"The Model Will Be The Specification"* (Ericsen Slide 16). This approach has the potential to eliminate the need for expensive, full scale demonstrations. However, there are a number of things required for it to succeed.

- Physics-Based models
- Modeling standards
- Benchmark models
- Public library of models
- A body of international volunteer experts for all of the above
- Real-time simulation is needed for real hardware
- High speed real-time simulation is needed for high-speed controllers

(Ericsen Slides 19, 20 and 21)

The key parameter that has to be solved in the design of new ships is voltage. (Ericsen)

High-voltage, high-power building blocks are needed for continued improvement of PCS. The attributes required are:

- Packaged building blocks with functional specifications
- Programmable to serve multiple applications
- Can be connected in series and parallel to achieve higher ratings

(Hingorani Slide 22)

PEBB (Power Electronic Building Blocks) are devices that sense what they are plugged into and what is plugged into them. They make the electrical conversion needed via software programming. The functions contained in software include the inverter, breaker, frequency converter, motor controller, power supply, and actuator controller. PEBBS are an important approach to reduce the cost of custom design of new components. (Hingorani Slide 16)

B. New Topologies

Fuel cell power plant voltage limits are determined by the stack electrical isolation design or the voltage difference across all the cells in the stack relative to ground. A low fuel cell stack voltage differential is desired to minimize stack electrical isolation requirements, reduce fuel cell cost and simplify design. On the other hand, higher fuel cell stack voltage (to 750V, or even 1000V) is desired to minimize the cost of the PCS by reducing inverter cost and size and also by enhancing inverter efficiency. Connecting pairs of stacks in small (<2 MW) distributed generation power plants in series minimizes stack-to-ground voltage and maximizes inverter voltage input. (Berntsen Slides 2 and 3).

One approach to collecting DC current from the fuel cells in these small power plants is to use a DC bus that is fed by a multitude of stacks. This has the advantage of providing optimal KVA matching of inverters, and the capability of part-load operation with failed inverters and stacks, which results in a significant cost saving. However, this system has no ability to bias individual stack currents, which results in less than optimal fuel flow, power diode losses, and the expense of custom work on the DC bus. (Berntsen Slide 5)

In general, the relatively low voltage output of fuel cell stacks limit PCS options for multi-megawatt, multi-fuel cell stack systems envisioned for IGFC power plants. Common mode voltage can be a problem. The presence of high frequency common mode voltage with respect to ground contributes to circulating ground currents which can interfere with ground fault protection and also contribute to neutral shift and electromagnetic interference. Enjeti discussed the pros and cons of four topologies identified below, that can be used for large IGFC plants.

Topology	PCS Configuration
# 1	2 fuel cell stacks (350V) series connected & center point grounded, one dc-dc converter followed by a 3-level inverter to produce 2300V 3-phase ac
# 2	4 fuel cell stacks (350V) series connected in pairs and center point grounded, two dc-dc converters with outputs connected in series, followed by a 3-level inverter to produce 4160V 3-phase ac
# 3	Each fuel cell stack (350V) connected to a dc-dc converter with isolation, followed by a 1-phase LV inverter. Several such modules are connected in cascade to form one MV ac system
# 4	Fuel cell stacks followed by dc-dc converter & 3-phase inverters. Several of these modules are combined together via 3-phase transformers to realize a multilevel inverter system for medium voltage.

(Enjeti Slide 30)

Enjeti found two different methods for reducing the magnitude of the circulating current: the use of a common mode filter and the introduction of a shielded high frequency transformer.

Another set of three possible topology options that can be used in large, IGFC power plants is summarized below:

- Low-voltage DC-AC inverter + low frequency transformer
- Low-voltage power electronics including DC-DC and DC-AC + cascaded inverters
- High-voltage power electronics including DC-DC and diode clamped multilevel inverters

High-power high-efficiency DC-DC converters are needed for multilevel inverter based fuel cell power plants. The options for high power DC-DC converters include:

- Full-bridge converter
- Multilevel converter
- Three-phase DC-DC converter
- V6 DC-DC converter

Multilevel inverters allow significant reduction on current ripples and their associated losses. Cost reduction can be realized with passive component size reduction. High-power SiC Schottky diodes are needed for most circuit configurations. (Lai Slide 25)

Each power converter module of a Cascaded Multilevel Inverter typically consists of a dc/dc voltage regulator and an H-bridge inverter. Single-phase, multi-phase, three phase wye or delta connections are possible. It can be used in many power applications (Ozpineci Slide 3)

The advantages and disadvantages of this system are summarized below:

Advantages	**Disadvantages**
• Modular – Reduced manufacturing and maintenance costs • Scalable – Reduced design cost • Fault tolerant operation – Increased availability – Redundant levels – Possible reconfiguration • Energy storage • Low harmonic distortion – Reduced filters	• Component count – Extra switches and transformers – Higher component cost – Low voltage components • More complicated control • Isolated dc sources

(Ozpineci Slide 4)

Other attributes include

- Synthesis of desired ac voltage from several levels of dc voltages
- More levels produce a staircase waveform that approaches a sinusoid
- Harmonic distortion of output waveform decreases with more levels
- No voltage sharing problems with series connected devices
- Low dV/dt reduces switching losses and EMI
- Multilevel PWM is possible

(Ozpineci Slide 6)

Mazumder proposed a novel hybrid modulation scheme for bulk power transmission. It is high frequency and scalable, but SiC-based components are necessary to achieve its advantages. This proposed topology has three stages of power conversion with the following features:

- A HF sinusoidal phase-shift-modulated zero-voltage turn-on full-bridge inverter, which interfaces to a low-voltage and high-current fuel-cell stack
- A three-leg diode rectifier that transforms the bipolar ac voltage at the secondary of the HF transformer to a unipolar pulsating waveform (which has a 6-pulse envelope)
- An ac/ac PWM converter that converts the pulsating output of the rectifier to a line-frequency ac output using hybrid modulation
- A three-phase HF transformer provides galvanic isolation, boosts the stack voltage, and enables series connection of multiple modules on the secondary for scalability. (Mazumder Slide 3, presentation not provided)

The advantages claimed for this high-frequency operation at higher power applications are significant reductions in electromagnetic and electrostatic component sizes. This leads to lower footprint space and labor cost and also simplifies topological structure, thereby increasing system reliability. (Mazumder Slide 11, presentation not provided)

Polyphase Resonant Power Conditioning is a new method to generate high voltages from low with very high power, which may have the potential to reduce those costs. The key characteristics are described below.

- Essentially a large (polyphase and resonant) DC-DC Converter
  - At least 1/10 size, weight, and volume of any previous method
- Uses recently proven technologies
  - Traction Motor Metallized Hazy Polypropylene Self-Clearing Capacitors for energy storage
  - Multi-megawatt capable Insulated Gate Bipolar Transistors
- Transformer cores of Amorphous Nanocrystalline Alloy
  - 1,000 times more efficient than steel
  - 1/300 core volume and weight for same power as 60Hz steel
- Polyphase resonant voltage multiplication to further minimize transformer volume and weight
- Easily scaleable to 10's of MW and 100's of kV

  - Easily optimized for various use (and lower power/voltage)
- Design is fault tolerant and inherently self-protective
  - Protect systems not necessary
  - Permits long cable lengths and remote location (Reass I Slide 4)

The present and future capabilities of Polyphase Resonant Conditioning are described below:

- IGBT Long pulse systems demonstrated
  - 140 kV, 1 MW Average (10 MW Long-Pulse)
  - Efficiency ~94%
- IGBT CW systems to 10 MW realizable
  - Efficiency ~97% possible
  - Similar footprint to SNS system
  - Does not require increase in component current or voltage ratings
- Medium pulse MOSFET (10 – 100uS) to 2.5 MW, 250 KW Average
  - 50 kV, 50 Amp, 250 KW Average
  - Small and compact
  - Agile in voltage, pulse width, and rep-rate
- Semiconductors still limiting technology at these power levels

(Reass I Slide 16)

C. New Materials

The only new material discussed at the Workshop for improving the performance of PCS components was silicon carbide (SiC). Wide band gap materials such as SiC have the potential to positively impact the performance of:

a. Power Circuits
b. Power Components, active and passive
c. Signal Electronics
d. Control
e. Software
f. Thermal Management
g. Mechanical Design & Packaging

SiC devices are not drop in replacements for Si devices. Achieving their full benefit comes from addressing all areas of the system that are impacted.(Casey Slide 11)

The use of SiC devices has the potential for allowing radically different choices in PCS topology. Among the attributes of SiC are:

- SiC Schottky diodes minimize reverse-recovery losses as compared to Si PiN diodes;
- Thus, SiC unipolar/bipolar power devices can enable high-frequency operation for high-voltage and high-power applications, which offer choices radically different than provided by IGCT. Currently, Northrup Grumman and

Cree are working on 13.5 kV, 10 kHz SiC MOSFETs and JBS. Purdue is working on even higher voltage SiC bipolar transistors;
- Further ability to withstand higher voltage without compromising switching and conduction losses and thermal sustenance can lead to simpler topological structures

(Mazumder Slide 2, presentation not provided)

Quantitatively, the advantages of SiC properties over Si currently used in many typical devices are:

- 10 times higher Breakdown Field than Si allows
  - Tradeoff higher breakdown voltage
  - Lower specific on-resistance
  - Faster switching
- 3 times higher Thermal Conductivity than Si allows higher current densities
- 3 times higher Bandgap than Si allows higher temperature operation

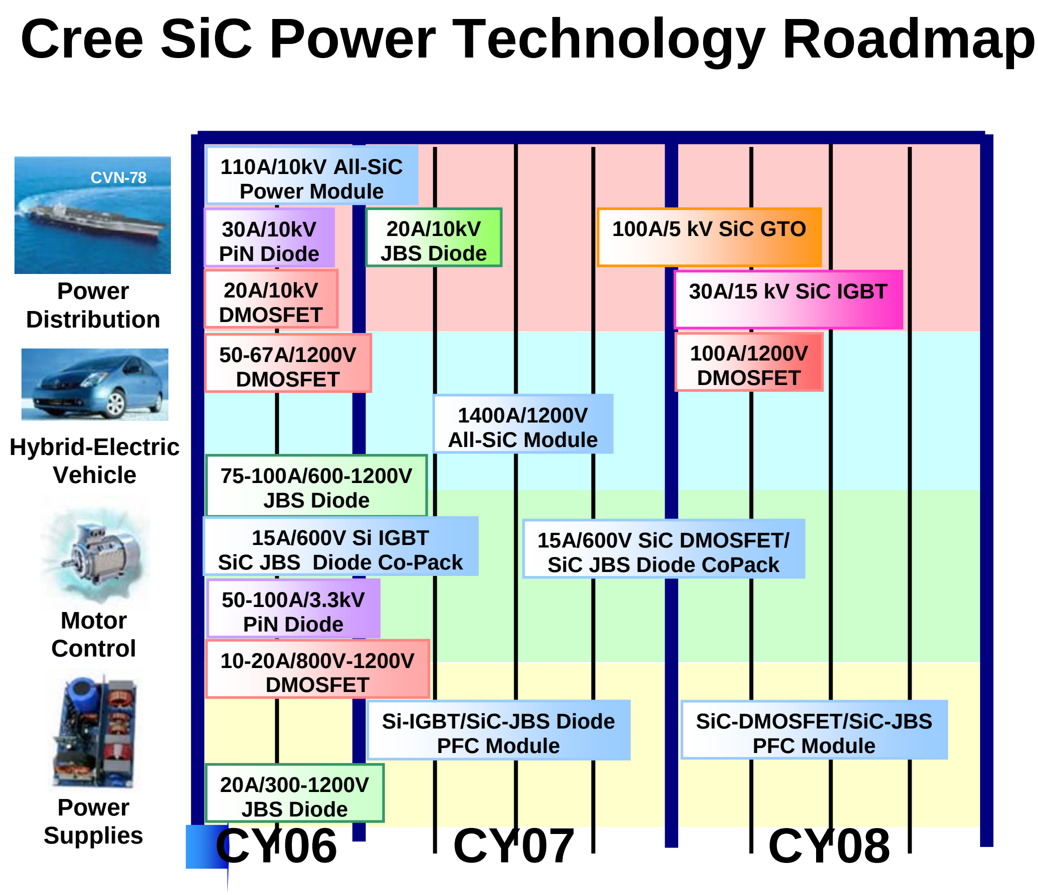
(Grider Slide 3)

Among the devices containing SiC components that are currently under development are:

- DIMOSFETs
- UMOSFETs
- Vertical JFETs
- IGBTs
- BJTs
- Thyristors/GTOs

These devices are listed in order of increasing voltage, decreasing speed, and increasing operating temperature (Grider Slide 7)

The following planned schedule for delivering SiC-component containing devices to the market was presented by Cree.



(Grider Slide 32)

D. New Components

The focus of component development for future PCS must be on the achievement of:

- Significant Reduction in:
  - Cost
  - Losses
  - Size
  - Weight
- Significant Improvement in Switching Frequency

(Hingorani Slide 18)

Discussion at the workshop covered inverters, transformers, capacitors and integrated devices as specific components in PCS.

i. Inverters

One of the current major markets for inverters is solar power systems. The cost of 100 inverters for these systems is in the range of 7-10% of total solar system cost or about

$500/kW for the complete inverter package. The total number of parts in that package is over 200. The total cost of $500/kW is allocated as shown below, based on the Bill of Materials for that system. The cost of the semiconductor power components represents 4% of the total costs of the parts in the inverter.

Inverter Package Component	Fraction of Bill of Materials Cost, $/kW
Inverter power components (Si-based)	4
Other inverter components (gate drives, bus caps, some of the bus work, heat removal, some protection components, and connectors	14
Most of the protection, thermals, mechanicals, and connectors	10
Displays and interfaces to work with the control, balance of protection, and heat removal	7
Power supplies and its protection and isolation	5
Transformer	20
Box	10
Controller	10
Filter	20
Total	100

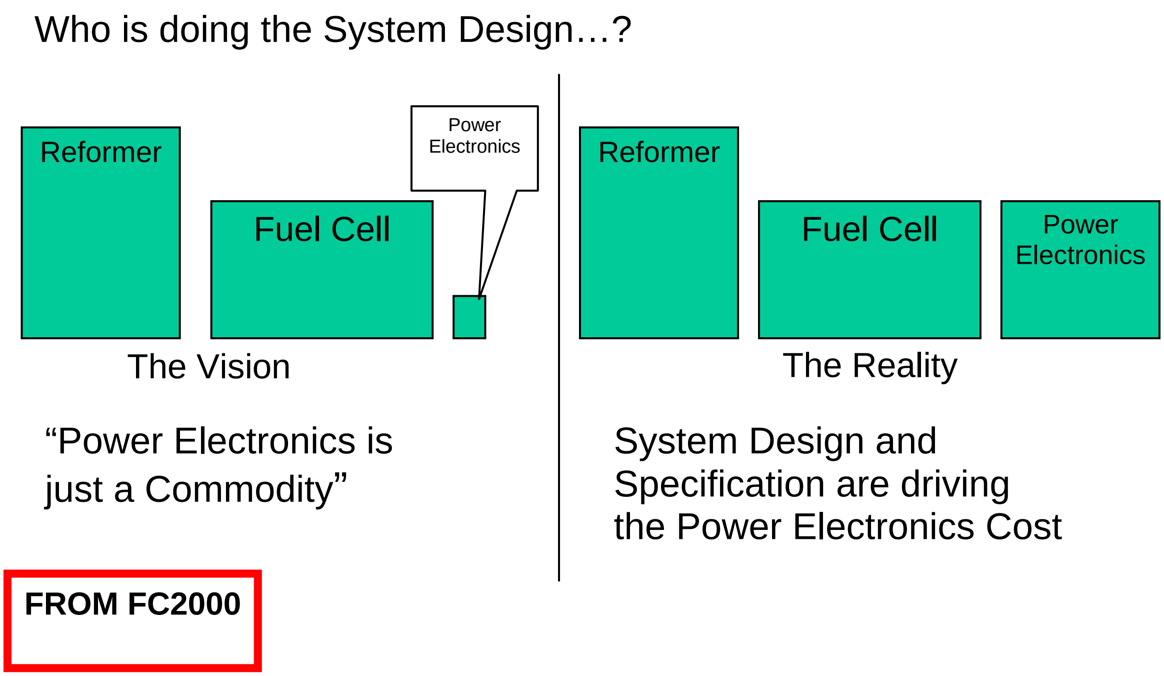
(Casey)

A comparison below shows how the parts cost breakdown would change if Si components were changed to SiC components

	Today's Si Design	Hybrid Si/SiC-1	Hybrid Si/SiC-2
Semiconductors	4.11	6.81	6.81
Magnetics	9.83	4.91	2.455
Filter Caps	1.7	0.85	1.7
Heatsinks + Hardware	2.4	1.2	1.2
Fans	1	1	1
Sum (% of total parts cost)	19.04	14.77	13.165

A significant fraction of the costs of these inverters for solar power system applications is associated with the capabilities necessary to connect the solar power system to the grid. (Casey) Working with utilities to change those standards could result in a reduction of inverter complexity and parts count, which would significantly reduce the inverter system cost. Scaling up from the sizes used in solar power systems to high megawatt sizes anticipated in IGFC power plants should also result in a significant reduction in inverter costs.

As indicated in the following illustration, the early vision of fuel cell developers was that the PCS in a fuel cell power plant would represent a minor cost component. The reality is that the PCS represents a very significant cost because of the small scale of current fuel cell power plants and the limited market size.



(Casey)

The inverter issues for DOD markets are somewhat different than they are for solar power markets and include the following:

- Power density
- Switch power and voltage capability
- Pulsed operation/thermal management
- Present devices designed for continuous operation
- Internal connections and thermal designs should permit full utilization of the material in the device under pulsed operation
- Cost
- Advantages of lower weight and volume of an advanced switch needs to be accompanied by a reduced cost per kW

(Staines I Slide 3)

ii. Transformers

The costs of transformers represents a significant fraction of the total PCS cost. High frequency power transformer designs now provide a viable method to significantly reduce the physical size, weight, and footprint, as compared to conventional 60 Hz power transformers. (Reass II Slide 2)

The following conclusions apply to this system:

- C-core designs probably best for multiphase (more than 3) systems
  - Can drop single phase to continue operation
- Advanced core designs probably best for demanding requirements at mid-power levels using a 3 phase converter topology
- Winding techniques are also important
  - Reduce leakage inductance
  - Reduce field stresses

(Reass II Slide 23)

iii. Capacitors

Film capacitors are commonly used for Power Conversion:

- Depending on frequency, capacitors can be the largest component in the system
- Requirements are
  - Low inductance
  - High rms current capability
  - Low loss
  - 100% reversal
  - High energy density
  - GA-ESI paper/polypropylene capacitors developed for SNS

(Staines II Slide 2)

Significant R&D is under way to improve film properties. Currently polypropylene film capacitors have highest energy density at low temperature, but performance degrades rapidly above 40^{o}C. Investigations of high-temperature films including Polyphenyl sulfide (PPS), and Polyetheretherketone (PEEK), and Polyetherketoneketone (PEKK) are in progress.
(Staines II Slide 4)

Improvements in capacitor capability could impact converter costs as follows:

- High energy density passive components reduce the need for high frequency switching
- Reduces switching loss and switch stress
- Could use cheaper, more mature switch technology without prohibitive size, weight
- Metallized film capacitors fail gracefully
- Capacitor monitoring could identify when maintenance is required to avoid failures

(Staines II Slide 6)

iv. Integrated Devices

Power semiconductor module integration has the potential to further reduce the cost of converters. Significant progress, as detailed below, has been made:

- Trends in IGBT Chip Technology
  - Size, Voltage, Power Losses & Frequency
  - Impact on Packaging
- Intelligent Power Modules
  - Integrating Gate Drive & Protection Features in the Module Package
- System in a Module
  - Further Integration of System Components within a Module Package
- High Voltage Power Modules
- Integrating Chip Cooling in the Module
- Integrated Power Sub Systems

(Leslie Slide 2)

An Integrated "Intelligent" Power Module or "IGBT + Smarts" would have the following capabilities included:

- Gate drive, temperature sensing & protection elements are integrated in the power switch package
- Protection for:
  - Overtemperature
  - Overcurrent & short circuit
  - Low/high gate supply voltage
  - Fault signal feedback
- Improves switch performance since protection functions are integrated in package (Leslie Slide 8)

Further assembly of subsystems onto the chip could include:

- Power switches
- Energy storage devices
- Current sensing
- Gate drives
- Protection
- Cooling

(Leslie Slide 18)

5. Grid Connection Issues

The owners of electricity transmission systems set the technical requirements for interconnection to the AC grid, such as the amount and frequency of harmonics, circuit protection, and islanding. These requirements were developed for interconnection of relatively small solar powered systems, and somewhat larger wind systems. They are based on the requirements for connecting a relatively small scale distributed generation system to the grid. The requirements lead to additional investment in the PCS to meet those requirements. With a central station system producing multi-hundreds of MW, some of these requirements may be unnecessary and can be eliminated, thereby, reducing the required level of investment for the PCS system. For example, can the cost of small scale harmonic filtering required for small distributed generation PCS be eliminated in central station PCS applications? (Berntsen)

The technology for transmission of large quantities of electricity is evolving with increases in the number of HVDC and FACTS long distance transmission systems. HVDC and FACTS are complementary solutions. FACTS and HVDC controllers have been developed to improve the performance of long distance AC transmission. Later their use has been extended to load flow control in meshed and interconnected systems. (Tang Slide 25)

One example proposed for a new approach to integration of wind generation farms into the transmission grid may be preferred because obtaining transmission Right-Of-Way now can take much longer than building the wind farms. Underground DC transmission with voltage sourced converters could have lower cost, improved system integration, and much smaller permit and construction time. (Hingorani Slide)

The Workshop did not include anyone from the utility or transmission grid sector in attendance that could address the interconnection issues. It was felt that the Roadmap development should include people with that background.

6. IGFC Systems

DOE is funding development of fuel cell systems that would be incorporated into large central station, coal-gasification based power plants with capacities of hundreds of MW. The assumption is that these systems would be available for commercial deployment in 2020. The technology base for these plants will include commercial experience with IGCC plants, commercialization of SECA fuel cells and a significant test of 10-40 MW module island in a FutureGen-type IGCC plant. Design bases are being established for these power plants under DOE R&D contracts including the PCS section. The DOE cost goal for the entire Power Island, which will produce more than 50% of the power with fuel cells, and the bulk of the remainder with gas turbines, is $400/kW. The PCS for the Power Island has a cost goal of $40/kW. It is anticipated that IGFC plants will run fully loaded at steady state since they will be the most efficient coal plant on any utilities' system.

Current Fuel Cell Energy (FCE) products include 250 kW, 1 MW, and 2 MW Molten Carbonate Fuel Cell (MCFC) systems for distributed generation applications. Since the fuel cell stacks are relatively low voltage systems with individual stack voltages likely to be less than 500V, there are many options available to increase the output voltage to the level of the 18 kVA grid.

Overall system costs could be reduced by going to higher stack voltages, but the current, relatively low, price of 1200V IGBT's used in currently offered MCFC products makes it uneconomic to go to higher voltages in the rest of the system. The cost of the PCS amounts to about 10% of the cost of the current MCFC fuel cell product offered by FCE.

One option being considered by FCE to lower the cost of the PCS in their current product is to connect stack pairs in series. Among the issues being considered is the use of a common DC bus or dedicated/segregated PCS for individual stacks. Among the considerations for the use of a DC bus in high MW applications are:

- How many inverters can be eliminated?
- If inverters were produced at high volume and, therefore, lower cost, would the cost savings resulting from their elimination offset the added cost of a DC bus?
- In high MW applications, the value of efficiency improvements may allow higher investment in the PCS. (Berntsen)

Under its contract with DOE, Siemens is developing a design for a 100 MW IGFC power plant module. Each fuel cell in the module has an output of 1.5 MW. By using relatively small modules, it is possible to maximize current loading of the individual fuel cells. Two fuel cells are paired with the pair producing approximately 1000 VDV and 1000 amperes. The output from a single pair is fed to a, yet to be defined, 3 MW Electronic Power Converter (module controller). Four 3MW pairs make up a 12 MW block. Three 12 MW blocks are combined into a large block. Multiple large blocks are combined to reach the desired level of total power plant output.

The problems that a PCS design for this system must cope with include a 2:1 ratio of maximum fuel cell voltage to open circuit voltage, poor terminal voltage regulation under load, and the use of parallel inverters that can result in current flow surges and phase angle changes due to variations in voltage. Consolidating current on the DC side-position inverters at higher voltage can avoid AC problems. (Gordon Slide 6)

Any PCS topology selected:

- Must aggregate power from many fuel cell modules
- Must support individual current loading of the fuel cell modules … (or minimum groups)
- Should permit individual modules and electronics to be taken off line while the system continues to run … (or minimum groups)
- Deal with DC voltages that are not tightly uniform
- Must integrate AC power from other generators used to recover exhaust heat energy

(Gordon Slide 8)

The conclusions from the system analysis work to date are that:

- A complete system circuit design with the component means and the network for power consolidation is required to answer the $/kW question for the high megawatt converter
- Once a complete system circuit design is mad, costing can be done and performance and cost tradeoffs for various elements can be evaluated

(Gordon Slide 19)

7. NIST/DOE Project for Evaluation of PCS Options for IGFC Power Plants

DOE and NIST have entered into an Interagency Agreement (IA) to have NIST lead an independent analysis of the expected impact of advanced PCS technologies on future IGFC power plants. Various conversion approaches that focus on the use of advanced technologies for low-voltage, medium-voltage, and high-power converters are being evaluated to determine areas requiring substantial federal government investment to meet the cost and efficiency goals of the SECA FutureGen Power Plant.
(Hefner I Slide 3).

The approach and boundary conditions being used for this study are 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 18kVAC, and assume transformer from 18 kVAC to transmission level voltage
- Boundary conditions and performance parameters:
  - FC Stack: center tap ~700 VDC, 1000 A
  - Individual FC stack current control (may be necessary for FC reliability)
  - Fault tolerant and serviceable
- Converter cost components:
  - Semiconductors
  - Module Packaging
  - Cooling System
  - Magnetics: Filter Inductors and HF voltage isolation transformers
  - Transformer up to 18kV
  - Breakers

(Hefner I Slide 5 and 6)

The initial baseline for the study is a center tapped fuel cell (approximately 700 VDC 0.6 MW) with a DCDC current regulator, a 480 VAC inverter, and 60 Hz transformers to raise the output voltage to 18 kVAC. 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 DCDC regulator and 480 VAC inverter functions into a single converter stage that uses the “present lowest-cost” switching power device, a 1200 V IGBT module.
(Hefner I Slide 8)

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 Schottky diodes are becoming common place in computer server power-factor-correction circuits. 1200 V SiC MOSFET switches and 1200 V hybrid SiC-Schottky/Silicon-IGBT modules are also expected in the near future.
(Hefner I Slide 10)

The second class of power converters being evaluated uses a DCDC converter to step the voltage up to 6 kV and a medium-voltage inverter is used to produce 4160 VAC, then a transformer is used to raise the voltage to 18 kVAC. In this case, the DCDC 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.
(Hefner I Slide 11)

Various semiconductor options exist for medium-voltage inverters including HV-IGBTs, 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, 3000 A IGCT's have been introduced that provide improved 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 multi-level 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 DARPA HPE program would enable the use of a single level inverter with a much lower part count and lower filter inductance requirements.
(Hefner I Slide 12 and 13)

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 DCDC converter and DCAC inverter functions and thus realizes different benefits from advanced semiconductors, magnetics, and capacitors. For example, architectures requiring DCDC converters with high voltage-gain or 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.
(Hefner I Slide 14 and 15)

After the briefing on the approach being considered for the impact study and on the individual power converter technologies, the workshop participants were asked during an open discussion session to provide feedback on additional specifications and technologies to be aware of 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)
  - EMI requirements
- Other advanced component technologies
  - Nano-crystalline magnetic materials for high-gain and voltage isolated converters
  - Packaging and advanced cooling systems
  - Interconnects and modularity
  - Capacitors (Dry Q cap: low cost, low maintenance)

(Hefner II Slide 2)

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 FC DC regulator
  - Ripple requirement - <3% for frequencies < 1kHz
- Year 2020 FC may be 2000 V (center-tap)

(Hefner II Slide 3)

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.

8. Formation of Roadmap Committee

The Workshop participants were asked to develop a consensus in regard to each of the questions listed below. Their consensus responses to each question are summarized below.

Question 1: Are there new materials, devices, and topologies that would accelerate the achievement of the cost and performance requirements for power conversion systems for these markets?

Consensus 1: Yes

Question 2: Should a Roadmap process be organized to support achievement of this objective?

Consensus 2: Yes. The Workshop participants agreed that a Roadmap process be initiated to offer guidance for further development of PCS that could meet the requirements for more cost effective and more efficient power conversion. A number of those present expressed a willingness to serve on such a committee and, in addition, the names of other potential committee members were proposed. Satcon agreed to take a leadership role in the formation of the committee. The proposed names are listed below.

Leo Casey, Satcon (Leader)
Le Tang, ABB
Siemens
FCE
NIST
Frank Holcomb
ORNL
Utilities (TVA, AEP, National Grid, SCE)
EPRI
Jason Lai
Prasad Enjeti
ARL (Ed Schaefer)
OSD

Question 3: Should it work down from topologies (market pull) or up from materials (technology push)

Consensus 3: It is too early to reach a decision on that question

Question 4: Should subcommittees be organized by market thrust, product power capacity, time frame of development, or some other basis?

Consensus 4: It is too early to reach a decision on that question

Question 5: Would the formation of an Interagency Task Force on this subject be of value?

Consensus 5: It would probably be useful at this time. There is an Interagency Committee in place that deals with power.

9. List of Workshop Presentations

High Megawatt Converter Workshop
January 24, 2007
NIST Headquarters
Gaithersburg, MD

Berntsen
George Berntsen, Manager Electrical and Controls Engineering, Fuel Cell Energy; ***Needs and Wants-Suggestions for High Voltage and High Megawatt Applications***

Casey
Denny Mahoney and Leo Casey, Satcon; ***High-Megawatt Converter Technology Workshop, January 24, 2007***

Enjeti
Prasad Enjeti, Power Electronics Laboratory, Texas A&M University; ***High-Megawatt Converter Technology Workshop for Coal-Gas Based Fuel Cell Power Plants***

Ericsen
Terry S Ericsen, Office of Naval Research, Advanced Electric Power Systems Thrust; ***Model-Based Specification and Simulation-Based Design and Procurement***

Gordon
Tom Gordon, Siemens; ***DOE High-Megawatt Converter Technology Workshop***

Grider
David Grider, Anant Agarwal, Brett Hull, Jim Richmond, Mrinal Das, Bob Callanan, Jon Zhang, Joe Sumakeris, Al Burk, Mike O'Loughlin, Adrian Powell, Mike Paisley, and John Palmour, Cree, Inc.; ***Recent Developments in SiC Power Technology at Cree***

Hefner I
Allen Hefner, NIST; ***High Megawatt Fuel Cell Power Converter Technology Impacts Study (NIST/DOE Interagency Agreement)***

Hefner II
Allen Hefner, NIST; ***Discussion of High Megawatt Fuel Cell Power Converter Technology Impacts Study (NIST/DOE Interagency Agreement)***

Hingorani
High-Megawatt Converter Technology Workshop

Holcomb
Franklin H. Holcomb, ERDC-CERL; ***DoD / Army Stationary Power Requirements-Secure, Reliable, Efficient Energy, Home Station to Foxhole***

Jones
Edward Jones, DOE Office of Clean Power Systems; ***Advanced Technology Goals for High Megawatt Applications***

Lai
Jason Lai, Future Energy Electronics Center, Virginia Tech ***Multilevel Converters for Large-Scale Fuel Cell Power Plants***

Leslie
Scott Leslie and John Donlon, Powerex, Inc.; ***Power Module Packaging & Integration***

Mazumder
Sudip K. Mazumder, Director, Laboratory for Energy and Switching-electronics Systems University of Illinois, Chicago; ***A High-power High-frequency and Scalable Multi-megawatt Fuel-cell Inverter for Distributed Generation***, presentation not provided

Ozpineci
Burak Ozpineci, Power Electronics and Electric Machinery Research Center, Oak Ridge National Laboratory; ***Cascaded Multilevel Inverters for Aggregation of Fuel Cells***

Reass I
W. A. Reass, D. M. Baca, and R. F. Gribble, Los Alamos National Laboratory; ***Possible Needs And Applications Of Polyphase Resonant Converters***

Reass II
W. A. Reass, D. M. Baca, and R. F. Gribble, Los Alamos National Laboratory; ***Multi-Megawatt High Frequency Polyphase Nanocrystalline Transformers***

Staines I
Geoff Staines, General Atomics – Electronic Systems Inc.; ***High-Voltage, High-Megawatt Power Requirements at GA***

Staines II
Geoff Staines, General Atomics – Electronic Systems Inc.; ***Capacitor Technology for High-Megawatt Power Conversion***

Tang
Le Tang, ABB US Corporate Research; ***Enhanced Power, Reliability and Efficiency in New HVDC and FACTS Development***

Wolk
Ron Wolk, Wolk Integrated Technical Services; ***Roadmap Development-High Megawatt Converters for Commercial Scale Applications***

10. Appendices

Appendix A. Workshop Agenda

Time	Activity	Invited Speakers
8:00 AM	Breakfast	
8:20	Welcome	Al Hefner
8:25	Keynote	Sam Biondo, DOE Office of Clean Power Systems
8:30	1. Federal Needs and Wants to Support Federal Advanced Technology for High Megawatt Applications	Edward Jones, DOE Office of Clean Power Systems Frank Holcomb, DOD/Army/ERDC-CERL Terry Ericsen, DOD/Navy/ONR
9:30	2. Industry Needs and Wants-Suggestions for High Voltage and High Megawatt Applications	Leo Casey, Satcon Le Tang, ABB George Berntsen, FCE Tom Gordon, Siemens
10:30	Break	
10:45	2. Continued	Geoff Stains, GA-SEI Bill Reass, LANL Nari Hingorani - HVDC Transission and MVDC Distribution
11:30 AM	3. Analysis of High Megawatt Fuel Cell Power Converter Technology impacts	Al Hefner, NIST DOE/NIST InterAgency Agreement • Analysis of impacts of new technologies • Synopsis of topologies and component technologies to be considered • Inputs needed from converter community
Noon	Lunch	
1:00 PM	4. Advanced Power Converter Technologies a. Topologies and Controls	Prasad Enjeti, Texas A&M -- Common Mode & IGCTs Jason Lai, Virginia Tech --Multi-level Inverters Sudip Mazumder, University of Illinois, Chicago Borak Ozpineci, ORNL - Cascade Multilevel
2:15 PM	b. Components, Power Semiconductors, Power Package/Module and Cooling, Passives	Dave Grider, Cree – SiC High Power Devices Scott Leslie, Powerex - IGBT Packaging and Integration Geoff Stains, GA-ESI - Capacitors William Reass, LANL - Nano-magnetics
3:15 PM	Break	
3:30 PM	5. Discussion of Technologies to be Considered in Impact Study	Al Hefner, NIST - Facilitator
3:45 PM	6. Roadmap development and government role	Ron Wolk, WITS - Facilitator Organize Roadmap Committee
4:45 PM	Wrap-up	
5:00 PM	Adjourn	

Appendix B. List of Workshop Participants

Name	Affiliation	Email	Telephone
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Ron Wolk	Wolk Integrated Technical Services (WITS)	ronwolk@aol.com	408-996-7811

Invited Participants Who Were Unable to Attend

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Appendix C. Workshop Invitation
High-Megawatt Converter Technology Workshop
January 24, 2007
National Institute of Standards and Technology (NIST)
Building 215-AML, Room C103-C106
8:00 AM -5:00 PM

Invitation

DOE Office of Clean Power Systems, U.S. Army Construction Engineering Research and Development Center (ERDC), and NIST invite you to participate in this one-day Workshop on High Megawatt Converter Technology.

Background,

On May 10, 2006, a Workshop was held to discuss possible approaches to lower cost Power Conditioning Systems that are based on newer topologies that take advantage of higher inverter voltages and faster switching frequencies and advanced materials such as the use of SiC to replace Si in existing devices.

One of the outcomes of the May 10, 2006 Workshop was a DOE-NIST Interagency Agreement to support the analysis and simulation necessary to make consistent quantitative predictions of the overall life-cycle cost reduction that can be obtained using advanced topologies, components, and materials.

Objectives

Another Workshop is planned for January 24, 2007 that will provide a forum to review Federal and Industry Wants and Needs for High Megawatt Applications and to discuss the planned Interagency Agreement efforts. The desired outcome of the Workshop is the organization of a roadmapping exercise to define the R&D required to support the future availability of significantly lower cost High Megawatt converters for use in a variety of applications including but not limited to Integrated Gasification Fuel Cell Power Plants.

The planned Workshop Agenda along with the List of Speakers and the List of Invited Participants are included on the attached pages.

Registration

Please RSVP with name, affiliation, email address, and phone number to Ron Wolk (ronwolk@aol.com) to confirm attendance. In order to be admitted to the NIST site, any Workshop participant that is not a US citizen must submit Form NIST 1260 to Terri Kroft (terri.kroft@nist.gov) at least 48 hours prior to the Workshop.

Speaker Instructions

We are asking each speaker to limit the formal presentation to 15 minutes and include primarily high level summary material. Additional, more detailed, backup material can be included (but not presented) for distribution to the audience and publication in the Workshop proceedings.