Proceedings of the High Megawatt Power Converter Technology R&D Roadmap Workshop

April 8, 2008
National Institute of Standards and Technology
Gaithersburg, MD

Sponsored by
DOE Office of Clean Energy Systems
National Institute of Standards and Technology
US Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL)

Prepared By

Ronald H. Wolk
Wolk Integrated Technical Services
San Jose, CA

November 1, 2008

<u>DISCLAIMER OF WARRANTIES AND LIMITATIONS OF LIABILITIES</u>

Table of Contents

List of Abbreviations

AC	Alternating Current
ERDC-CERL	US Army Engineer Research and Development Center, Construction Engineering Research Lab
DC	Direct Current
DG	Distributed Generation
DIMOSFET	Dielectric Metal-Oxide-Semiconductor Field Effect Transistor
DOD	Department of Defense
DOE	Department of Energy
ESWG	Electrical Systems Working Group
FACTS	Flexible AC Transmission System
FC	Fuel Cell
GW	GigaWatt
HF	High Frequency
HVDC	High Voltage Direct Current
HV	High Voltage
IAPG	Inter-Agency Advanced Power Group
IGBT	Insulated Gate Bipolar Transistor
JBS	Junction Barrier Schottky
kHz	kiloHertz
kV	kiloVolt
kVA	kiloVolt Ampere
kW	kiloWatt
MOSFET	Metal-Oxide-Semiconductor Field Effect Transistor
MVA	MegaVolt Ampere
MW	MegaWatt
NIST	National Institute of Standards and Technology
PCS	Power Conditioning System
R&D	Research and Development
SECA	Solid State Energy Conversion Alliance
SOFC	Solid Oxide Fuel Cell

1. Summary

A High Megawatt Power Converter Technology R&D Roadmap Workshop was held on April 8, 2008 at NIST headquarters in Gaithersburg, MD. Forty seven people who are active in the field participated.

The objective of the Roadmap Workshop was to initiate an effort led and supported by a broad spectrum of industry, to provide guidance in the development of advanced technologies required for future high-megawatt power conditioning systems (PCS) and more specifically the High Megawatt (HMW) power converter aspects of those PCS.

Twelve formal presentations covered the highest priority issues that should be addressed in developing a well-structured Roadmap that will serve the full spectrum of power generating and delivery markets. These issues included:

- Public expectations that are driving electricity supply and delivery choices
- Characteristics of the present large-scale power delivery grid
- Impact of the rapidly increasing amount of renewable energy that is processed in Power Conditioning Systems (PCS) being fed into the grid
- PCS needs for future alternate/clean energy sources
- Attributes of High Megawatt (HMW) power converters that can improve grid capacity and reliability
- PCS needs for the future power grid
- HMW converter technology development issues
- Regulatory changes needed to accommodate advanced HMW converter technology

The Workshop participants developed the following consensus positions (*in bold italicized print)* on five specific issues including:

- Role of converters in the grid of the future -- ***The attributes of advanced HMW converters will allow the grid to function more reliably and deliver many ancillary benefits that are not possible with today's converter technology***
- Key development requirements to go from 1 MW to 100/200 MW converter -- ***Lower cost SiC materials and SiC power semiconductor devices are needed to enable broad markets to develop***
- Other requirements to go from 1 MW to 100/200 MW converter systems – ***Regulatory standards for grid operation need to be changed to allow maximum benefits to be realized from development of SiC based advanced HMW converters.***
- Potential role of the Roadmap effort within IEEE – ***The IEEE should be involved in the Roadmap process.***
- Potential Role of the Roadmap effort within DOE – ***DOE should be invited to participate in the industry-led Roadmap process***

In response to a call for volunteers to serve on a formal Roadmap Committee, 14 of the meeting attendees responded affirmatively.

The following recommendations for the Roadmap process were adopted by consensus:

- The commonalties of different HMW converter applications must be identified. A literature search would be the first step.
- A summary of related activities, such as all programs in the "Smart Grid" activity should be summarized
- Coordination should be established with the Electrical Systems Working Group (ESWG) of the Interagency Advanced Power Group (IAPG)
- Focus the Roadmap on the achievement of R&D goals that can have a major impact. For example
    - Production of SiC-based components at a cost that will enable market development
    - High band-width power converters
    - Communication control and standards

2. Introduction and Background

Previously, on January 24, 2007, a group of forty-two Power Conditioning Systems (PCS) experts invited by National Institute of Standards and Technology (NIST), Department of Energy (DOE) Office of Clean Energy Systems and ERDC-CERL assembled at a High Megawatt Converter Workshop held at NIST headquarters in Gaithersburg, MD. An Organizing Committee consisting of Dr. Samuel Biondo (DOE), Dr. Allen Hefner (NIST) and Frank Holcomb (ERDC-CERL) recommended the invited participants and presenters for that workshop. Among the objectives of the High Megawatt Converter Workshop were to discuss the material presented that focused on the current state-of-the-art approaches to design of those 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 this issue, and to discuss the merits of setting up a industry-led Roadmap Committee to offer guidance that could facilitate the achievement of the desired goals. (See www.high-megawatt.nist.gov/workshop-1-24-07/).

The January 24, 2007 High Megawatt Converter Workshop participants agreed that an industry-led Roadmap process should be initiated to offer guidance for further development of PCS that could meet the requirements for more cost effective and more efficient power conversion; hence the initiation of the High Megawatt Power Converter Technology R&D Roadmap Workshop. There was also a consensus at the High Megawatt Converter Workshop that an interagency task group should be formed to discuss how federal resources could potentially be utilized in a coordinated effort to address high-megawatt PCS needs. Subsequently, activities of the Interagency Advanced Power Group (IAPG) - Electrical Systems Working Group (ESWG) have been initiated to in part address this recommendation. Additionally, an NSF Workshop on Power Conditioning for Alternate Energy Systems was held on May28-29, 2008, to address the basic research and educational needs in this area.

A number of those present at the January 24, 2007 High Megawatt Converter Workshop expressed a willingness to serve on the committee to initiate the industry-led Roadmap process. Dr. Leo Casey of SatCon Inc. agreed to serve as the Chairman of an ad-hoc committee formed to organize a Roadmap Workshop. The other members of this ad-hoc committee were Dr. Allen Hefner (NIST) and Frank Holcomb (ERDC-CERL). Based on the recommendations of the January 24, 2007 workshop, the ad-hoc committee organized the High Megawatt Power Converter Technology R&D Roadmap Workshop, which was held on April 8, 2008 at NIST headquarters in Gaithersburg, MD.

The objective of the Roadmap Workshop was to initiate an effort led and supported by a broad spectrum of industry to provide guidance in the development of advanced technologies required for future high-megawatt power conditioning systems (PCS). Applications for these advanced PCS technologies include but are not limited to large-scale, high-power converters for connecting alternate/clean energy sources to the power grid, as well as converters for grid energy storage systems and advanced power transmission/distribution systems involving flexible ac transmissions (FACTS) and high-voltage dc (HVDC) transmission.

The expected outcome of the High Megawatt Power Converter Technology R&D Roadmap Workshop was insights and perhaps even answers to the following questions:

- What are the potential commercial barriers to advancement and application of grid connected power converters?
- Which enhanced performance attributes of advanced converters would provide economic value to specific market segments?
- Are there common performance attributes that would serve multiple markets?
- What is the worth of these attributes to each individual user, local grid, NERC region, or the US as a whole
- What are the technology gaps?
- What are the specific R&D efforts needed to fill those gaps and accelerate successful commercialization?
- What are the specific dates of the required successful R&D to support these estimated economic benefits?
- What is the estimated cost of that R&D and the resulting Cost/Benefit ratio?
- What are the supply chain industries and time frame required for specific supply chain developments?
- How can a roadmap process be established to provide guidance for the development and application of advanced grid connected power converters?
- What funding sources are available to support development of this story?

The key objective of this second High Megawatt Converter-related Workshop was the formation of a Roadmap Committee, which was accomplished.

3. Overview of Technical Presentations

The presentations covered the highest priority issues that should be addressed in developing a comprehensive Roadmap for High Megawatt Power Converters R&D that will serve the full spectrum of power generating and delivery markets. These issues included:

- Public Expectations That Are Driving Electricity Supply And Delivery Choices
- Characteristics Of The Present Large-Scale Power Delivery Grid
- Impact Of The Rapidly Increasing Amount Of Renewable Energy That Is Processed In Power Conditioning Systems (PCS) Being Fed Into The Grid
- PCS Needs For Future Alternate/Clean Energy Sources
- Attributes Of High Megawatt (HMW) Power Converters That Can Improve Grid Capacity and Reliability
- PCS Needs For The Future Power Grid
- HMW Converter Technology Development Issues
- Regulatory Changes Needed To Accommodate Advanced HMW Converter Technology

Public Expectations That Are Driving Electricity Supply And Delivery Choices

The American public expects electricity delivery networks that are resistant to outages, markets that are functional in delivering electricity at fair prices, carbon-emission free electricity, and a coherent national energy policy. More than 70% of the electricity supplied to this market is now generated by coal (50%) and nuclear (20%) power plants. Both of these options are creating public concerns at this time regarding additional power generation plants. There is strong public and legislative pressure to increase the use of renewable fuels, and to reduce carbon emissions. State-specific Renewable Portfolio Standards exist that mandate the amounts of renewable power to be delivered to customers in those states and schedules for reaching those requirements have been implemented in 29 states.

Characteristics Of The Present Large-Scale Power Grid

The electricity supply of the entire US and parts of Canada is delivered through three major power grids – the Eastern Interconnection (EI), Western Interconnection (WI), and the Texas Interconnection (TI). The largest of these is the EI which has been referred to as the largest single machine in the world covering 2,000,000 square miles with a capacity of 925,000,000 HP. The major functions of these grids are to:

- Instantaneously deliver electricity that is produced in hundreds of widely separated power plants in each interconnection area whenever demanded by the customers in each of these huge areas

- Collect and utilize information on energy flows and power characteristics to maximize the efficiency of the delivery process.

There are a number of technical issues that characterize these grids:

- They deliver large amounts of power efficiently
- They have enormous fault clearing capabilities
- Control is very broad, covering very large areas
- Generation must instantaneously equal demand in each control area
- There is no storage
- The overall system is slow in terms of the response rate of prime movers and controls as well as fault clearing, protection and coordination
- Load shedding is the only relatively quick response function but does not prevent initial transmission overload
- Generation can trip as a result of unstable frequency within a very narrow range

The system works well most of the time, but disturbances are hard to predict in advance. Occasionally, there are spectacular failures that result in blackouts across very wide areas. The last of these, which occurred in 2003 on the EI, originated with a problem in Ohio and resulted in blacked out areas in New England, Mid Atlantic, Midwest, and Southern states, as well as parts of Eastern Canada. The responses by regulating bodies included calls for more transmission capacity, more central station generation, and looser relays to prevent premature generator trips. In contrast, there is another approach that utilizes the emergence of distributed generation resources such as wind and solar at the moment and in the future fuel cell systems, all equipped with High Megawatt converter systems that reduce grid instability, as the basis for solving the problem.

As one example of the emergence of additional distributed generation, the US Army is moving in the direction of increasing the on-site generated fraction of the total electric power that they consume. This is part of an effort to develop on-site microgrids at their main and forward deployment bases. These systems will incorporate the use of renewables to the extent practical.

Impact Of The Rapidly Increasing Amount Of Renewable Energy That Is Processed In PCS Being Fed Into The Grid

The amount of renewable energy-based distributed power generation is increasing rapidly although it still constitutes a small fraction of total US generation. DOE has established a future target of 20% for the amount of total energy generated from renewables. In terms of the MW level of power delivered to the grid, wind is the fastest growing resource. For example, 6000 MW of wind generation is now in operation in Southwest Wyoming. 100-500 MW wind farms are being developed in wind-rich areas across the US. In Denmark, wind power constitutes 20% of the total power supply.

The intermittent nature of wind power does cause problems with the grid at this time.

Wind power is erratic, often from moment to moment and most importantly the variability of supply is destabilizing to the grid. European blackouts have been caused by wind tripping off the line. Many of the currently deployed wind machines use induction generators, which are low cost but cause instability problems, and have poor power factors and ride-thru capabilities. By contrast, wind turbines with doubly fed induction generators can actually supply reactive power (VARS) which can be controlled. Future wind systems will utilize permanent magnet, variable speed generators with fully rated inverters, which will eliminate many of these problems. The addition of energy storage components to wind generator networks is critical to realizing the full value of wind power.

Costs for solar systems remain very high. Recent estimates by Southern California Edison (SCE) are that the cost of individual home roof-top photovoltaic (PV) systems is about $8000/kW and larger commercial scale systems cost about $5000/kW prior to tax credits. SCE is embarking on a major program to install 50 MW/year of solar thermal during a five year period (totaling 250 MW) in the Mohave Desert near Barstow, CA.

The growing supply of intermittent power from wind and solar means either that the power from these resources has to be conditioned to meet current grid requirements or those requirements have to be changed to minimize the cost of meeting those standards in a way that will not jeopardize either grid efficiency or stability

PCS Needs For Future Alternate/Clean Energy Sources

MW to HMW PCSs are necessary to provide power grid connection for fuel-cell based clean energy systems, alternate energy sources such as wind and solar, and the energy storage systems necessitated by the intermittent nature of sources such as wind and solar. The specific PCS needs differ with the type of alternate/clean energy source, although there are many common requirements: Alternate/clean energy sources typically produce low voltage unregulated DC power or AC power that is not synchronized with the grid. The PCS must enable efficient and reliable operation of the power source units, and provide high voltage regulated/synchronized power meeting requirements for grid connectivity. Large scale central station plants (> 100 MW) also require a power collection bus or network to collect the power from many megawatt scale source units within the plant. High collection bus voltages (18 kV, 3-phase AC, for example) may reduce the cost the collection network but may also require either high voltage inverters or additional step-up transformers.

For example, future central station Integrated Gasification Fuel Cell (IGFC) coal plants, consisting of many Solid Oxide Fuel Cell (SOFC) modules, will require a HMW PCS to collect the low voltage DC power produced by the fuel cell modules and convert the power to the very much higher voltage levels necessary for delivery to the grid at the transmission level (> 265 kV AC). The SOFC modules produce unregulated power at approximately 1000 V DC and require low 60 Hz ripple current to extend the lifetime of the modules. The IGFC plant PCS will also need to provide the ability to service and maintain the individual SOFCs without shutting down the plant. HMW PCSs may also be required for ancillary systems within IGFC plants including electric drives for high speed CO_2 storage compressors.

Large central station wind plants have similar HMW PCS requirements for collecting power from many wind towers and for converting the power to the much higher voltage levels necessary for delivery to the grid at the transmission level or sub-transmission level (> 60 kV AC). Wind turbines operating asynchronously with the power grid enable higher efficiency but require the PCS to provide the synchronized 60 Hz AC voltage necessary for connection to the power grid. In addition to the high voltage needs for the collection network, the weight and size of the power converter on the wind tower imposes an additional constraint for the PCS. Large offshore wind plants also require long lifetime fault tolerant converters that will enable the turbines to operate with infrequent service intervals.

Distributed generation, consisting of megawatt to multi-megawatt scale wind and solar generators for example, requires PCSs that connect to the grid at the distribution level (e.g., 13.8 kV AC). The PCSs for distributed generation may also provide added value such as source monitoring and grid support functions such as dispatchability and supplying reactive power. In general, the increased reliance on PCSs for renewable energy based distributed power generation and the associated storage systems and grid controllers will require new approaches to reduce PCS cost, increase functionality, and extend PCS lifetime warranties.

Attributes of High Megawatt (HMW) Converters that Can Improve Grid Capacity and Reliability

The addition of dispersed power generators that contain relatively large PCS with HMW can provide multiple benefits that could contribute to improved grid operation and stability. HMW converters are enabling technology for grids to:

- Control flows
- Accommodate faults faster
- Implement energy storage
- Improve control so that the grid can be decomposed into smaller, more manageable pieces

Fully rated converters can enhance real and reactive power (P, Q), power ramp rates, frequency stability, phase balance and the like. Specific areas of improved performance are that these DG resources are:

- Remotely controllable
- Supply both real power and reactive power

- Provide active damping (stabilizing), fault clearing, rapid damping of dynamics, active filtering, harmonic cancellation, overcurrents during fault, capable of being deliberately unbalanced

Advanced HMW converters that include much improved control capabilities can offer additional features including:

- Dispatchable real power
- Dispatchable reactive power,
- Controllable harmonic cancellation
- Phase balancing
- Controllable inertia
- Controllable trip point
- Permissive utility controlled islanding
- Controlled flows
- Faster fault clearing
- Storage

PCS Needs For The Future Power Grid

Historically, the grid has been used primarily to transmit Alternating Current (AC) power. More recently, the cost of High Voltage Direct Current (HVDC) equipment for long distance DC transmission has fallen below that of comparable AC equipment. For example, 800 kV DC transmission is now 1/3 cheaper than AC for a 750 mile transmission line. More and more, long-distance HVDC transmission systems are being installed around the world. PV and fuel cell systems produce DC power directly, which is usually converted to AC power for injection into the grid. Keeping the energy DC may not only be an option, it may be very attractive both technically and economically.

Grid stability depends largely on the rate of frequency change. High inertia equipment such as steam turbines, gas turbines, and nuclear plants help to slow down the rate of frequency change and to increase stability. The combination of DG generation and storage, interconnected to the Grid through fully rated inverters, can have very high equivalent inertia that is therefore useful in blackout prevention. HMW components in such a system contribute to overall system stability as do back-to-back DC and high impedance AC links.

The smart Grid initiatives are largely focused on improved sensing and control to achieve more effective grid management, particularly in improving the capacity factor. Better sensors and actuators, particularly aimed at sub-cycle responses, are needed to improve information flow from the grid to allow better decisions to be made faster.

One concept suggested for improving grid stability is to separate the grid into smaller pieces and to allow islanding of those smaller pieces to prevent problems cascading through a larger segment of the grid. Essentially this approach allows for a distressed grid to break into multiple microgrids that can resynchronize and recoalesce at a later time.

HMW Technology Development Issues

Development of a large, commercial market for HMW converters in the future will require that costs be reduced to the $40-200/kW range depending on the application, warranties will be for at least 10 years, switching capability will exceed 5 kHz, and efficiency will be at least 97%. Today, commercially available converters are more costly than this target and are not yet sufficiently reliable to economically support the requirement for 10 year warranties recently mandated in California.

Silicon carbide (SiC) is considered to be an enabling material to replace conventional silicon (Si) components to facilitate improved HMW characteristics. SiC enables higher switching frequency, higher temperature and higher voltage operation. The higher electric field strength of SiC compared to that of Si enables development of devices with much higher switching speed for a given voltage requirement (e.g., 10 kV SiC devices switch at 20 kHz compared to the 200 Hz limit of today's 6 kV Silicon switching devices).

The capability of switching at high voltage (e.g., 15 kV) and high frequency (e.g., 20 kHz) should permit the elimination of 60 Hz AC transformers in HMW converters, which today represent some 30% of the system cost, and so significantly reduce the cost of that unit. However, today's cost for high voltage, high frequency (HV-HF) SiC power devices is still too high for widespread market penetration. Improvements in yield and the availability of larger wafers with acceptable defect concentrations are required to reduce SiC chip costs to the lower levels required for broad market success. Availability of active devices from multiple commercial vendors is a new and very encouraging sign of progress in this area.

Currently, 600 V to 1.2 kV SiC power Schottky diode products with currents in the range of 20 A are widely available with a market size that is increasing at about 50% per year. These devices have significantly cut losses in commercial power factor correction circuits while also demonstrating field reliability exceeding that of the Silicon power diodes. 1.2 kV SiC MOSFET and JFET switch devices are also beginning to be introduced to the market and are expected to advance rapidly.

Recently, the DARPA Wide Bandgap Semiconductor Technology (WBST) High Power Electronics (HPE) Phase 2 program has successfully scaled SiC MOSFET and Schottky diode power device technology to produce 10 kV, 100 A, 20 kHz SiC half bridge power modules that will be used to demonstrate a 13.8 kV, 2.7 MVA Solid State Transformer in the ongoing HPE Phase 3 program. Future development of SiC bipolar type devices such as IGBTs and PiN diodes may also enable devices with voltage ratings exceeding 15 kV.

There are a number of technology challenges facing developers of HV-HF power module packages: These include:

- External voltage strike and creep
- Internal dielectrics-reliability losses, corona/partial discharge
- High temperatures
- Low inductance -- power loop, gate loop
- Efficient cooling -- High chip power densities

With the emergence of the HV-HF semiconductor devices comes the need to advance the other passive power electronic technologies necessary to operate at higher voltage, power and frequency. For example, high-frequency transformers require orders of magnitude less magnetic material and copper than 60 Hz transformers but require advanced magnetic materials (e.g., nanocrystalline magnetic materials) to facilitate low cost manufacturability.

In the area of passive components, there has been significant progress in the development of:

- Amorphous nanocrystalline transformers
  - Higher quality, wider belts of winding materials and better manufacturing technology
- High power capacitor improvement
  - Self-healing metallized hazy polypropylene energy storage is much more compact and reliable than high voltage (paper and foil) method
  - Record energy densities in polypropylene pulse power capacitors
- High power resistors made from reticulated carbon

Regulatory Changes Needed To Accommodate Advanced HMW Converter Technology

Present standards on anti-islanding and tight trip points can both inhibit the introduction of new DG technology and prevent the Grid obtaining the full benefit of these resources. For example, the trip point of conventional turbines is much lower at 57 Hz than IEEE 1547 standard, which is now set at 59.6 Hz. Open standards are required to facilitate the integration of DG technology with the grid. Some of the key roadblocks have been removed by utilities in Europe to make this happen.

4. Consensus on Key Technical and Organizational Issues for the Roadmap Process

The Workshop participants developed the following consensus positions on five topics including:

- Role Of Converters In The Grid Of The Future
- Key Development Requirements To Go From 1 MW To 100/200 MW Converter Systems
- Other Requirements To Go From 1 MW To 100/200 MW Converter Systems
- Potential Role Of The Roadmap Effort Within IEEE
- Potential Role Of The Roadmap Effort Within DOE

Role Of Converters In The Grid Of The Future

Electricity generating companies are beginning to recognize the potential ancillary benefits that can be obtained by improved grid interaction and operation. For example, 100 MW Static VAR compensators are being added by utilities. Some utilities in the eastern US are buying selling small quantities of VARS. Excel Energy has made a $5 M investment in NaS batteries for energy storage. Dynamic VARS can be produced by wind generators and peaking turbines and can also be produced by grid connected inverters for DG or Storage integration.

There are a large number of inherent attributes that larger and faster HMW converters would offer to improve interaction between electricity generators and the grid and operation of the grid itself. These include positive impacts on:

- Spinning reserve
- Voltage regulation
- VARS
- Sag mitigation
- Active filtering (harmonics)
- Ramp rates
- Storage
- Phase balancing

The attributes of HMW converters need to be considered in relation to the entire system. For example, the use of high-bandwidth components (such as HV-HF SiC devices) offers capabilities of real time control of real and reactive power on grid. The use of high bandwidth power converters increases transmission line capability through stability enhancements and to access useable transmission thermal capability within loss constraints. HMW converters offer significant capabilities in the future to support separate islands on the grid and the establishment of microgrids.

The use of larger HMW converters in distributed generation systems provides the technical capabilities to implement the concept of using smaller control areas and deliberate islanding of those areas to avoid widespread blackouts.

Standards need to be established to deal with the following HMW issues within the converters and the grid:

- Safety
- Communications
- Interconnection

At this time regulators do not appear to fully recognize the value of HMW attributes. In order for the benefits to be realized by consumers, regulators have to be educated about the potential value of these benefits. DOE EERE is working on quantifying the value of these attributes. Markets need to be developed for the ancilliary services of HMW converters so that the value of these benefits can be bought and sold.

Currently, there is a shortage of students being trained in this field. The number of trained people needed by industry to support the design and development of HMW converter applications is not adequate to meet the demand. The associated NSF Workshop on Power Conditioning for Alternate Energy Systems was initiated and held on May 28-29, 2008 to address the basic research and educational needs in this area.

Key Development Requirements To Go From 1 MW To 100/200 MW Converter Systems

The market requirements that must be met for larger, HMW converters are:

- Lower cost
- Better reliability
- Higher bandwidth converter capability
- Monetize and realize economic value of ancillary services

The technology improvements necessary to support scale-up of HMW converter systems are:

- Low cost and high reliability SiC-based components
- Better plastics in packaging that lasts more than 10-15 years.
- Better control systems for converters
- Better simulation models need to support system development

Other Requirements To Go From 1 MW To 100/200 MW Converter Systems

There are a number of regulatory and market issues that need to be addressed to support development of HMW converter systems including:

- Need to evolve from existing utility requirements
- Need standards that can accommodate attributes of advanced converters
- IEEE 1547.3 communication standards specific to DG
- SiC producers need guidelines in terms of what SiC based products to develop
- Micro-grids should have eight 9's reliability

Potential Role On The Roadmap Effort Within IEEE

The IEEE has subcommittees on islanding; one that focuses on generators > 10 MW and another on intentional islanding. Both of these committees may have interests in this Roadmap effort. It was recommended that an overview of this Workshop be presented at the IEEE PES national meeting in Pittsburgh in July. Unfortunately this was not accomplished.

Potential Role On The Roadmap Effort Within DOE

DOE has $100 Million/year available to support demonstration of smart grid technologies. They should be invited to be involved in the development of this Roadmap. DOE is developing fuel cells for the power blocks of future near zero emissions central station coal plants, with requirements for low-cost, high efficiency DC-AC converters.

5. Formation of Roadmap Committee

In response to a call for volunteers to serve on a formal Roadmap Committee, 14 people responded affirmatively. They were:

Leo Casey, SatCon, Chairman of the Ad-Hoc Committee
Maric Begovic, IEEE, Georgia Tech
George Berntsen, FCE
Sumit Bose, GE Energy
Lee Fingersh, NERL
Dave Grider, Cree
Al Hefner, NIST
Frank Holcomb, US Army CERL
Jason Lai, Virginia Tech
Madhav Manjrekar, Siemens
Bob Reedy, Florida Solar Energy Center
Alex Stankovic, Northeastern University
Le Tang, ABB
Charlie Vartarian, Southern California Edison

Several approaches to actually developing the Roadmap were discussed. The following recommendations were adopted by consensus:

- The commonalties of different applications must be identified. A literature search would be the first step. E.g., advanced HMW converters for large compressors for applications in near-zero emissions coal plants
- A summary of related activities, such as all programs in the "Smart Grid" activity should be summarized
- Coordination should be established with the Electrical Systems Working Group (ESWG) of the Interagency Advanced Power Group (IAPG). Activities of IAPG ESWG have been initiated to in part address this need.
- Focus the Roadmap on the achievement of R&D goals that can have a major impact. For example
    - Production of SiC at much lower cost
    - High band-width power converters
    - Communication control and standards

6. Responses to Key Workshop Questions

The Workshop participants were asked to give their responses to 11 questions that had been posed in the invitation to the Workshop. The responses of seven individuals (identified by lower case letters) who responded to some or all of the questions are listed below.

1. What are the potential commercial barriers to advancement and application of grid connected power converters?

   a. High voltage (10 KV and higher) SiC power devices and modules require market volume to justify investment. Currently, most commercial SiC power device markets are lower voltage (600V-1.2 kV)
   b. Cost, regulatory issues, performance/reliability, successful demonstration, <u>standards</u>
   c. Performance, reliability, and cost
   d. Regulations that conflict and/or don't match needs in reality
   e. Costs, standards
   f. Need to modify regulations, but still make sure that the grid remains reliable and stable.
   g. Module devices – cost and reliability issues for 10kV to 22kV modules

2. Which enhanced performance attributes of advanced converters would provide economic value to specific market segments?

   a. SiC power devices and modules offer
      - Higher efficiency
      - Higher switching frequency
      - Higher temperature at reduced cooling requirements
   b. VAR, single phase control, flexible coms, interchangeability
   c. VAR, frequency, power quality, voltage support for transmission level and distribution level applications
   d. Ride-through, VAR support, harmonic cancellation, flicker mitigation
   e. Controls for load shedding and powerflow optimization
   f. Energy storage, harmonic correction, line balancing, power factor correction. Utilities would be the immediate beneficiary, but end users would ultimately benefit from lower costs and higher reliability.

3. Are there common performance attributes that would serve multiple markets?

   a. SiC power device and module technology will have application in solar cell converters, wind turbines, power grid, hybrid vehicles. Most commercial markets are 600V-1.2 kV.

b. Standardize on AC voltage, communications
c. VAR, frequency, power quality, voltage support for transmission level and distribution level applications

4. What is the worth of these attributes to each individual user, local grid, NERC region, or the US as a whole?

b. VARS and reliability are evolving markets. Utilities can face a financial penalty for poor performance, but there is no current "standard" charge.

5. What are the technology gaps?

a. High voltage (10 kV and higher) SiC power devices and modules.
b. Higher voltage devices and faster switching results in higher costs
c. Fast relays, switches, energy storage integration and control
d. SiC and related switches, mid-frequency high-power commercial inductors
e. For many of the applications, the technology exists. As components see a larger market, costs will come down to be more competitive. Obviously, further improvements would accelerate this effort.
g. HV module dielectrics – Potting compounds/gels with high temperature, high voltage and corona resistance

6. What are the specific R&D efforts needed to fill those gaps and accelerate successful commercialization?

a. R&D in High Voltage SiC devices and modules:
    - 10kV SiC MOSFETs
    - 12 kV and higher SiC IGBTs
    - SiC power modules
b. Need demonstration of technologies to demonstrate applications and economic studies to show value.
c. Government-led demonstrations
f. We need to start to develop actual equipment that can perform in the field, even though such equipment may not use the optimum devices (e.g. SiC, nano-transformers, etc.) In some cases this is being done, but it needs to be more widespread.
g. Programs and funding to address above dielectric issues, SiC device developments

7. What are the specific dates of the required successful R&D to support these estimated economic benefits?

a. Currently there is some DOD R&D investment in SiC power devices and modules. Further R&D investment is needed over the next 1 to 5 years.
b. Time is money. There is a cost for lost opportunities as utilities will tend to follow the norm. Match dates to other DOE/DOD targets.
c. Start now to be completed in 3-5 years.
g. As soon as possible

8. What is the estimated cost of that R&D and the resulting Cost/Benefit ratio?

   a. Need several million dollars per year.
   c. $5-6 million/year program for 3-5 years targeting specific technology gaps

9. What are the supply chain industries and time frame required for specific supply chain developments?

   a. High voltage (10 kV and higher) SiC power devices and modules needed to establish reliability and reduce costs to acceptable levels over five years.
   b. Components, packaging... Supply chain needs to demonstrate capability in prototypes and validate long-term pricing structure.

10. How can a roadmap process be established to provide guidance for the development and application of advanced grid connected power converters?

   a. Need to understand voltage, current, frequency requirements for SiC power devices and modules.
   b. Establish appropriate standards and consistent plan to move the technology forward.

11. What funding sources are available to support development of this story?

   a. DOD is currently the only major supporter of SiC power device and module technology R&D development. There are commercial SiC power device markets, but they are focused on lower voltage (600V to 1.2 kV) currently.
   b. DOE, SBIR, DOD, automotive industry, international organizations
   c. DOE-OE, EERE, NIST, DOD, DARPA? DOE-FE?

7. List of Workshop Presentations

High Megawatt Power Converter Technology R&D Roadmap Workshop
April 8, 2008
NIST Headquarters
Gaithersburg, MD

Bose
Sumit Bose, GE Infra, Energy; PCS Requirements for Wind

Casey
Leo Casey, Satcon; Keynote and Workshop Goals – Roadmap Vision; State of the art grid connected converter specifications and goals for future value added high megawatt grid connected converters

Gordon
Tom Gordon, Siemens; PCS Requirements for Fuel Cells

Grider
Dave Grider, Cree; SiC Power Devices and Material Technology

Hefner
Al Hefner, NIST; High Voltage, High Frequency Devices for Solid State Power Substation and Grid Connected Converters

Holcomb
Frank Holcomb, US Army ERDC-CERL; PCS Requirements for Army Micro Grid Programs

Leslie
Scot Leslie, Powerex; Advanced Power Module/Package Technology

Reass
Bill Reass – LANL Advanced Passive Component Technologies for High Frequency Power Converters

Reedy
Bob Reedy, FSEC; Power Conditioning Systems (PCS) Needs of Photovoltaic and Renewable Energy

Stankovic
Alex Stankovic, Northeastern University; Issues and Advantages for High Megawatt (HMW) Converters in Transforming the Power Grid

Tang
Le Tang, ABB US Corporate Research; PCS Requirements for HVDC and FACTS

Vartarian
Charlie Vartarian, SCE; Power Energy and Grid of the Future

8. Appendices

Appendix A. Workshop Agenda

Time	Activity
8:00 AM	Registration and Breakfast
8:30-8:35	Welcome and Logistics
8:35	a. Opening Presentations -- Session Chair, Leo Casey, Satcon b. Keynote and Workshop Goals – Roadmap Vision; State-of-the-art Grid Connected Converter Specifications And Goals For Future Value Added High Megawatt Grid Connected Converters (Leo Casey - Satcon) c. Power Energy and Grid of the Future (Charlie Vartarian – SCE) d. Issues and Advantages for High Megawatt (HMW) Converters in Transforming the Power Grid (Alex Stankovic – Northeastern University)
10:00	Break
10:15	2.0 Grid–connection of Alternate/Clean Energy Sources – Session Chair, Ron Wolk 2.1 Power Conditioning Systems (PCS) Needs of Photovoltaic and Renewable Energy (Bob Reedy – FSEC) 2.2 PCS Requirements for Wind (Sumit Bose – GE Infra, Energy) 2.3 PCS Requirements for Fuel Cells (Tom Gordon – Siemens)
11:10	3. Grid Controllers and Advanced Power Grid – Session Chair, Frank Holcomb 3.1 PCS Requirements for Army Micro Grid Programs (Frank Holcomb- US Army ERDC-CERL) 3.2 PCS Requirements for HVDC and FACTS (Le Tang – ABB)
12:15 PM	Lunch
1:30	4. Advanced Component Technologies for HMW Converters – Session Chair Al Hefner 4.1 High Voltage, High Frequency Devices for Solid State Power Substation and Grid Connected Converters (Al Hefner, NIST) 4.2 SiC Power Devices and Material Technology (Dave Grider – Cree) 4.3 Advanced Power Module/Package Technology (Scot Leslie – Powerex) 4.4 Advanced Passive Component Technologies for High Frequency Power Converters (Bill Reass – LANL)
3:00	Open Discussion on Technical and Organizational Issues – Moderator Leo Casey
4:00 PM	Wrap-up and Recording of Consensus Positions – Moderator Ron Wolk
5:00 PM	Adjourn

Appendix B. High Megawatt Power Converter Technology R&D Roadmap Workshop Participant List

Name	Affiliation	Email	Telephone
Tarek Abdallah	ARMY (CERL)	t-abdallah@cecer.army.mil	217-373-4432
Miroslav Begovic	Georgia Tech, PES	miroslav@ece.gatech.edu	404-894-4834
George Berntsen	FCE	berntsen@fce.com	203-825-6000
Sam Biondo	DOE Fossil Energy	samuel.biondo@hq.doe.gov	301-903-2700
Sumit Bose	GE Infra, Energy	bose@ge.com	
Alan Cookson	NIST	alan.cookson@nist.gov	
Leo Casey	SatCon Technology Corporation	leo.casey@satcon.com	617-897-2435
M. Chinthavali			
Charlton Clark	Sentech	cclark@sentech.org	240-223-5535 (direct)
Rajib Datta	GE	datta@research.ge.com	518-387-6852
Branislav Djokic	National Research Council of Canada	b_djokic@yahoo.com	
Lee Fingersh	NREL/NWTC	Lee_Fingersh@nrel.gov	303-384-6929
Gerald J. Fitzpatrick	NIST	Gerald.fitzpatrick@nist.gov	301-975-8922
Tom Gordon	Siemens	t.gordon@siemens.com	412-256-2590
David Grider	Cree, Inc.	David_Grider@cree.com	919-313-5345
Shantanu Gupta			
Al Hefner	NIST	hefner@nist.gov	301-975-2071
Dick Hockney	Beacon Power Corp.	hockney@beaconpower.com	978-661-2085
Frank Holcomb	US ARMY ERDC-CERL	Franklin.Holcomb@us.army.mil	217-373-5864
Alex Huang	North Carolina State Univ.	aqhuang@ncsu.edu	919-513-0404
Steve Jenks	DOE Fossil Energy		
Benjamin Karlson	Sandia	bkarlso@sandia.gov	505-803-3676
Lumas Kendrick			
Jason Lai	Virginia Tech	laijs@vt.edu	540-231-4741
Scott Leslie	Powerex	sleslie@pwrx.com	724-925-4482
Peter Leventopoulos	Mesta Electronics Inc.	pete.levo@mesta.com	412-754-3000 x203
Dennis P. Mahoney	SatCon Applied Technology	Dennis.Mahoney@satcon.com	617-897-2448
John Mandalakas,	Mesta Electronics, Inc.,	john@mesta.com	412-754-3000 ext.202

Madhav D. Manjrekar	Siemens Power T&D	madhav.manjrekar@siemens.com	919 961 7611
Jerry Melcher	Cree Inc.	jerrymelcher@wwc.com	858-437-2242
Ned Mohan	University of Minnesota	mohan@umn.edu	612-625-3362
Dave Nichols	Rolls Royce	david.nichols@us.rrfcs.com	614-755-2763
Joe Pierre	Siemens	Joseph.pierre@siemens.com	412-256-5313
William Reass	Los Alamos National Laboratory	wreass@lanl.gov	505-665-1013
Bob Reedy	FSEC	Reedy@fsec.ucf.edu	
Maria Reidpath	DOE NETL		
George Robinson	L-3 Communications	George.Robinson@L-3com.com	714-956-9200, ext. 143
Thomas Roettger	Northrop Grumman	thomas.roettger@ngc.com	410-552-2412
Wayne Surdoval	NETL	Wayne.surdoval@netl.doe.gov	412-386-6002
David Shero	Mesta Electronics Inc.	dave.shero@mesta.com	412-754-3000 ext.204
Alex Stankovic	Northeastern University	astankov@ece.neu.edu	
Le Tang	US ABB	Le.tang@us.abb.com	919-856-3878
Dan Ton	DOE	dan.ton@ee.doe.gov	202 586-4618
Bill Trac	DOE Fossil Energy	Bill.Trac@HQ.DOE.GOV	
Charlie Vartanian	SCE	charles.vartanian@sce.com	323-889-5516
Mark Williams	URS/EG&G	mark.williams@eg.netl.doe.gov	304-285-4344
Ron Wolk	WITS	ronwolk@aol.com	408-996-7811

Appendix C. Workshop Invitations

High-Megawatt Power Converter Technology R&D Roadmap Workshop
April 8, 2008
National Institute of Standards and Technology (NIST)
Building 215-AML, Room C103-C106
8:00 AM -5:00 PM

Planning Committee
Leo Casey, Chairman, (SatCon)
Al Hefner, (NIST)
Frank Holcomb, (US Army CERL)
Ron Wolk, Staff Support, (WITS)

Dear

This letter is an invitation to encourage your participation in a one-day Workshop to initiate a High-Megawatt Power Converter Technology R&D Roadmap.

DATE and LOCATION

The Workshop will be held at the NIST, Gaithersburg, MD, on April 8, 2008 from 8:30am to 5pm. Further details will be provided in subsequent correspondence.

OBJECTIVE

The objective of the workshop is to initiate a roadmapping effort led and supported by a broad spectrum of industry, to provide guidance in the development of advanced technologies required for future high-megawatt power conditioning systems (PCS). Applications for these advanced PCS technologies include but are not limited to large-scale, high-power converters for connecting alternate/clean energy sources to the power grid, as well as converters for grid energy storage systems and advanced power transmission/distribution systems involving flexible ac transmissions (FACTS) and high-voltage dc (HVDC) transmission.

BACKGROUND

Over the past two years an effort has been conducted with Government, Academia and Industry participation to identify technologies requiring development to meet the PCS cost and performance goals of the DOE Solid-State Energy Conversion Alliance (SECA) and DOE's Programs for near zero-emission fuel cell power plants. The High Megawatt Converter Workshop held on January 24, 2007 reviewed the federal and industry wants and needs for a wide range of high-megawatt PCS applications and discussed the merits of proposed approaches for achieving significant cost reduction and improved electrical conversion efficiency (www.high-megawatt.nist.gov/workshop-1-24-07/). The workshop participants reached a consensus that an interagency task group should be formed to discuss how federal resources could potentially be utilized in a coordinated effort to address high-megawatt PCS needs, and that an industry-led roadmapping effort should be initiated to offer guidance that could facilitate the achievement of the desired goals.

In response to the consensus reached at the High Megawatt Converter Workshop, an interagency working group meeting was held on September 13, 2007 to in part discuss federal programs for high-megawatt PCS. In addition, an effort in cooperation with NSF to identify power conditioning system challenges and educational needs associated with alternate energy systems and the power grid has been initiated.

By this invitation we seek to involve all key INDUSTRY stakeholders in these continuing efforts by establishing the technology roadmap necessary to provide guidance for programs that will lead to the achievement of the desired federal and industry high-megawatt PCS goals.

EXPECTED WORKSHOP OUTCOME

The workshop is expected to answer the following questions:

- What are the potential commercial barriers to advancement and application of grid connected power converters?
- Which enhanced performance attributes of advanced converters would provide economic value to specific market segments?
- Are there common performance attributes that would serve multiple markets?
- What is the worth of these attributes to each individual user, local grid, NERC region, or the US as a whole
- What are the technology gaps?
- What are the specific R&D efforts needed to fill those gaps and accelerate successful commercialization?
- What are the specific dates of the required successful R&D to support these estimated economic benefits?
- What is the estimated cost of that R&D and the resulting Cost/Benefit ratio?
- What are the supply chain industries and time frame required for specific supply chain developments?
- How can a roadmap process be established to provide guidance for the development and application of advanced grid connected power converters?
- What funding sources are available to support development of this story?

RESERVATION

Please RSVP with name, affiliation, email address, and phone number to Ron Wolk (ronwolk@aol.com or call 408-996-7811) to confirm attendance. Additional information regarding the workshop agenda and technologies to be discussed will be forthcoming.

PROPOSED AGENDA

8-8:30am	**Registration and Breakfast**
8:30 – 8:40am	**Keynote and Workshop Goals (Roadmap Vision)**
8:40 -10:10am	**Converters for grid-connection of Alternate/Clean Energy sources and storage systems**
10:10- 10:30am	**Break**
10:30- Noon	**Converters for grid conversion, control and conditioning: (VARS, inertia, spinning reserve, harmonics, phase balancing, local transient suppression, fault limiting/isolation, FACTS, HVDC, and Micro-grids etc.)**
Noon – 1pm	**Lunch**
1-2pm	**Converter design & manufacturing, status and trends (Today's state-of-the art as it determines: Cost, Efficiency, Ease of Installation and Service, Availability, Uptime, Reliability, Warranties, Outdoor Capable, Wide Operating Temperature Range, etc.)**
2-3pm	**Advanced Converter technology (driving to improve the critical operating metrics through Advance Semiconductors such as SiC, Advanced Magnetics and Capacitors, Prognostic Controls, Smart Grid Integration, etc.)**
3-3:20	**Break**
3:20-4:50 PM	**Open discussion of needs, potential benefits, and approaches for establishing a roadmap to offer guidance for stakeholder industries in developing and application of advanced high-megawatt converter.**
4:50-5pm	**Wrap-up**
Adjourn	**5:00 pm**