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

DISCLAIMER OF WARRANTIES AND LIMITATIONS OF LIABILITIES

This report was prepared by Wolk Integrated Technical Services (WITS) as an account of work sponsored by U. S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL), Champaign, IL.

WITS: a) makes no warranty or representation whatsoever, express or implied, with respect to the use of any information disclosed in this report or that such use does not infringe or interfere with privately owned rights including any party's intellectual property and b) assumes no responsibility for any damages or other liability whatsoever from your selection or use of this report or any information disclosed in this report.

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, standards
    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**

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 Terri 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
Tarek Abdallah	U.S. Army CERL	t-abdallah@cecer.army.mil	217-373-4432
Allie Auld	University of California, Irvine	aea@apep.uci.edu	949-824-1999 ext. 141
Peter Barbosa	ABB Corporate Research Switzerland	peter.barbosa@ch.abb.com	+41 58 586 7540
George Berntsen	FCE	berntsen@fce.com	203-825-6000
Sam Biondo	DOE-Fossil Energy	samuel.biondo@hq.doe.gov	301-903-5910
Leo Casey	Satcon	leo.casey@satcon.com	617-897-2435
Muhammad Choudhry	West Virginia University	machoudhry@mail.wvu.edu	304-293-6371 x 2524
Don Collins	DOE - NETL	donald.collins@netl.doe.gov	412-445-1320
Alan Cookson	NIST	alan.cookson@nist.gov	
Prasad Enjeti	Texas A&M	enjeti@tamu.edu	979-845-7466
John Donlon	Powerex	jdonlon@pwrx.com	724-925-4377
Terri Ericsen	ONR 334 Program Manager	ericset@onr.navy.mil	703-696-7741
Tom Gordon	Siemens	Thomas.gordon@siemens.com	*412-256-5313*
David Grider	Cree, Inc.	David_Grider@cree.com	919-313-5345
Allen Hefner	NIST	hefner@nist.gov	301-975-2071
Narain G. Hingorani	Consultant	nhingorani@aol.com	650-941-5240
Frank Holcomb	U.S. Army CERL	Franklin.H.Holcomb@erdc.usace.army.mil	217-373-5864
Edward Jones	DOE	edwardj@vt.edu	301-903-3913
Hans Krattiger	ABB	hans.krattiger@us.abb.com	919-856-3878
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
Sudip Mazumder	U. of Illinois, Chicago	mazumder@ece.uic.edu	312-355-1315
Ty McNutt	Northrup Grumann	ty.mcnutt@ngc.com	410-765-4772
Ned Mohan	University of Minnesota	mohan@umn.edu	612-625-3362
Kevin Motto	Northrup Grumann	kevin.motto@ngc.com	410-552-2366,
Burak Ozpineci	ORNL	ozpinecib@ornl.gov	865-946-1329
Joe Pierre	Siemens	Joseph.pierre@siemens.com	412-256-5313
Duane Prusia	Powerex	Dprusia@pwrx.com	724-925-4377

William Reass	Los Alamos National Laboratory	wreass@lanl.gov	505-665-1013
Thomas Roettger	Northrup Grumann	thomas.roettger@ngc.com	410-552-2412
Karl Schoder	West Virginia University	Karl.Schoder@mail.wvu.edu	304-293-0405 x 2541
David Shero	Mesta Electronics Inc.	dave.shero@mesta.com	412-754-3000, x204
Marc Sherwin	Northrop Grumman	Marc.Sherwin@ngc.com	*410-993-8318*
Mike Spence	WVU	mspence2@mix.wvu.edu	304-296-5971
Geoff Staines	General Atomics Electronic Systems	geoff.staines@ga-esi.com	858-522-8278
Wayne Surdoval	NETL	Wayne.surdoval@netl.doe.gov	412-386-6002
Le Tang	US ABB	Le.tang@us.abb.com	919-856-3878
Albert J. Tucker	Consultant	ajtucker@ieee.org	443-321-4719
Wayne Weaver	U.S. Army CERL	wayne.w.weaver@erdc.usace.army.mil	217-352-6511
Ron Wolk	Wolk Integrated Technical Services (WITS)	ronwolk@aol.com	408-996-7811

Invited Participants Who Were Unable to Attend

Sharon Beermann-Curtin	Program Manager Defense Advanced Research Projects Agency Defense Sciences Office	Sharon.Beermann-curtin@darpa.mil	571/218-4935
Bimal K. Bose	University of Tennessee-Knoxville	bbose@utk.edu	865-974-8398
Frank Goodman	EPRI	fgoodman@epri.com	650-855-2872
Richard D. Hepburn	SAIC	richard.d.hepburn@saic.com	703-676-1416
Yuri Khersonsky	Consultant	ykhersonsky@ieee.org	714-956-9200
Thomas Lipo	U. of Wisconsin at Madison	lipo@engr.wisc.edu	608-262-0287
John Pazik	Office of Naval Research	pazikj@onr.navy.mil.	
Steve Shaw	Montana State University	sshaw@ece.montana.edu	406-994-2891
Ralph Teichmann	GE Central R&D	Teichman@crd.ge.com	518-387-4488
Ricardo S. Zebulum	Jet Propulsion Laboratory	Ricardo.S.Zebulum@jpl.nasa.gov	818-354-7623

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.

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 Terri 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	

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.

January 24, 2007 High Megawatt Converter 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 Terri Ericsen, DOD/Navy
9:30	2. Industry Needs and Wants-Suggestions for High Voltage and High Megawatt Applications	Leo Casey, Satcon Ralph Teichmann, GE - absent 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 Panel Discussion
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 Organize Roadmap subcommittee
4:45 PM	Wrap-up	
5:00 PM	Adjourn	

Invited Participants

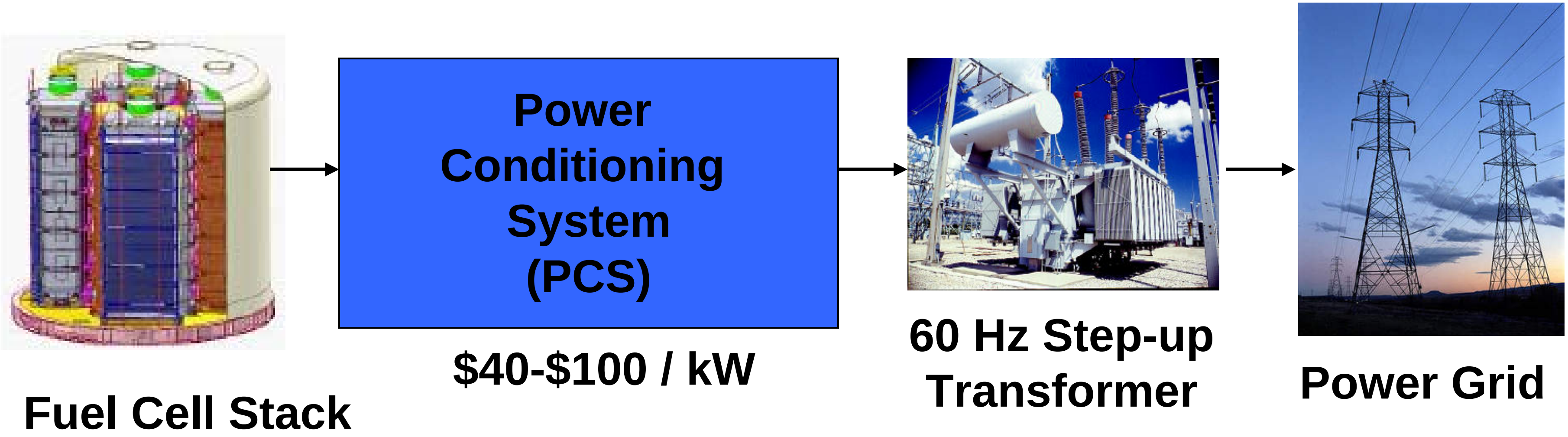
Name	Affiliation	Email	Telephone
Tarek Abdallah	US Army CERL	t-abdallah@cecer.army.mil	217-373-4432
Allie Auld	University of California, Irvine	aea@apep.uci.edu	949-824-1999 ext. 141
Peter Barbosa	ABB Corporate Research Switzerland	peter.barbosa@ch.abb.com	+41 58 586 7540
George Berntsen	FCE	berntsen@fce.com	203-825-6000
Sam Biondo	DOE-Fossil Energy	samuel.biondo@hq.doe.gov	301-903-5910
Bimal K. Bose	University of Tennessee-Knoxville	bbose@utk.edu	865-974-8398
Leo Casey	Satcon	leo.casey@satcon.com	617-897-2435
Muhammad Choudhry	West Virginia University	machoudhry@mail.wvu.edu	304-293-6371 x 2524
Don Collins	DOE - NETL	donald.collins@netl.doe.gov	412-445-1320
Alan Cookson	NIST	alan.cookson@nist.gov	
Prasad Enjeti	Texas A&M	enjeti@tamu.edu	979-845-7466
John Donlon	Powerex	jdonlon@pwrx.com	724-925-4377
Terri Ericsen	ONR 334 Program Manager	ericset@onr.navy.mil	703-696-7741
Frank Goodman	EPRI	fgoodman@epri.com	650-855-2872
Tom Gordon	Siemens	Thomas.gordon@siemens.com	412-256-5313
David Grider	Cree, Inc.	David_Grider@cree.com	919-313-5345
Allen Hefner	NIST	hefner@nist.gov	301-975-2071
Richard D. Hepburn	SAIC	richard.d.hepburn@saic.com	703-676-1416
Narain G. Hingorani	Consultant	nhingorani@aol.com	650-941-5240
Frank Holcomb	US Army CERL	Franklin.H.Holcomb@erdc.usace.army.mil	217-373-5864
Edward Jones	DOE	edwardj@vt.edu	301-903-3913
Yuri Khersonsky	Consultant	ykhersonsky@ieee.org	714-956-9200
Hans Krattiger	ABB	hans.krattiger@us.abb.com	919-856-3878
Jason Lai	Virginia Tech	laijs@vt.edu	540-231-4741
Scott Leslie	Powerex	sleslie@pwrx.com	724-925-4482
Thomas Lipo	U. of Wisconsin at Madison	lipo@engr.wisc.edu	608-262-0287
Dennis P. Mahoney	SatCon Applied Technology	Dennis.Mahoney@satcon.com	617-897-2448
Sudip Mazumder	U. of Illinois, Chicago	mazumder@ece.uic.edu	312-355-1315
Ty McNutt	Northrup Grumann	ty.mcnutt@ngc.com	410-765-4772

Ned Mohan	University of Minnesota	mohan@umn.edu	612-625-3362
Kevin Motto	Northrup Grumann	kevin.motto@ngc.com	410-552-2366,
Burak Ozpineci	ORNL	ozpinecib@ornl.gov	865-946-1329
John Pazik	Office of Naval Research	pazikj@onr.navy.mil.	Tbd on Monday
Joe Pierre	Siemens	Joseph.pierre@siemens.com	412-256-5313
Duane Prusia	Powerex	Dprusia@pwrx.com	724-925-4377
William Reass	Los Alamos National Laboratory	wreass@lanl.gov	505-665-1013
Thomas Roettger	Northrup Grumann	thomas.roettger@ngc.com	410-552-2412
Karl Schoder	West Virginia University	Karl.Schoder@mail.wvu.edu	304-293-0405 x 2541
Steve Shaw	WILL NOT ATTEND		
Marc Sherwin	Northrop Grumman	Marc.Sherwin@ngc.com	410-993-8318
Mike Spence	WVU	mspence2@mix.wvu.edu	304-296-5971
Geoff Staines	General Atomics Electronic Systems	geoff.staines@ga-esi.com	858-522-8278
Wayne Surdoval	NETL	Wayne.surdoval@netl.doe.gov	412-386-6002
Le Tang	US ABB	Le.tang@us.abb.com	919-856-3878
Ralph Teichmann	GE Central R&D	Teichman@crd.ge.com	518-387-4488
Albert J. Tucker	Consultant	ajtucker@ieee.org	443-321-4719
Wayne Weaver	US Army CERL	wayne.w.weaver@erdc.usace.army.mil	217-352-6511
Fei Wang	Virginia Tech. CPES	wangfred@vt.edu	540-231-8915
Ron Wolk	Wolk Integrated Technical Services (WITS)	ronwolk@aol.com	408-996-7811
Ricardo S. Zebulum	Jet Propulsion Laboratory	Ricardo.S.Zebulum@jpl.nasa.gov	818-354-7623

Welcome to

High-Megawatt Power Converter Technology R&D Roadmap Workshop

SECA Fuel Cell Plant



Fuel Cell Stack

Power Conditioning System (PCS)

$40-$100 / kW

60 Hz Step-up Transformer

Power Grid

$40-$100 / kW for PCS is a difficult stretch goal !

http://www.netl.doe.gov/publications/proceedings/07/SECA_Workshop/index.html

Previous Meeting :

High Megawatt Converter Workshop

January 24, 2007 at NIST

- **Industry Roadmap: Today**
  - **Initiate roadmap process to offer guidance for further development of high-megawatt converters technology**
- **Inter-Agency Advanced Power Group (IAPG)**
  - **Form interagency task group to coordinate Federal programs in high-megawatt converter technologies - under IAPG ESWG**
  - **Meeting at NIST - April 24-25, 2008**
- **National Science Foundation (NSF)**
  - **Establish power electronics curriculums and fundamental research programs for alternate energy power converters**
  - **Meeting at NIST - May 15-16, 2008**

High Megawatt Converter Workshop: http://www.high-megawatt.nist.gov/workshop-1-24-07/

High-Megawatt Power Converter Technology R&D Roadmap Workshop

AGENDA

8-8:30am	Registration and Breakfast
8:30-8:35	1.0) Welcome and Logistics: (Al Hefner and Ron Wolk)
8:35-10am	1) Opening Presentations (Session Chair: Leo Casey)
	1.1) Keynote and Workshop Goals -- Roadmap Vision; State-of-the-art grid connected inverter specifications and goals for future value added high-megawatt grid connected inverters (Leo Casey)
	1.2) Power, Energy, and Grid of the Future (Charlie Vartanian)
	1.3) Issues and Advantages for High Megawatt (HMW) Inverters in Transforming the Power grid (Alex Stankovic)

AGENDA (Late Morning)

10:15-11:10 **2) Grid-connection of Alternate/Clean Energy sources (Session Chair: Ron Wolk)**

2.1) Power Conditioning System (PCS) needs of Photovoltaic and Renewable Energy (Bob Reedy)

2.2) PCS Requirements for Wind (Sumit Bose)

2.3) PCS Requirements for Fuel Cells (Tom Gordon)

11:10-noon **3) Grid Controllers and Advanced Power Grid (Session Chair: Frank Holcomb)**

3.1) PCS requirements for Army Micro Grid Programs (Frank Holcomb)

3.2) PCS requirements for Power Island (Michel Ropp)

3.3) PCS requirements for HVDC and FACTS (Lee Tang)

AGENDA (Early Afternoon)

1-2:10pm 4) <u>Advanced Component Technologies for HMW Inverters</u>
(Session Chair: Al Hefner)

4.1) High-Voltage, High-Frequency Devices for Solid State Power Substation and Grid Connected Inverters
(Al Hefner)

4.2) SiC Power Device and Material Technology
(Dave Grider)

4.3) Advanced Power Module/Package Technology
(Scott Leslie)

4,4) Advanced Passive Component Technologies for High Frequency High Power Converters
(Bill Reass)

AGENDA (Late Afternoon)

2:10-3:40pm	**5) Open Discussion:** **(Moderator: Leo Casey)**	
	Technical:	- role of inverters in grid of the future - PCS for alternate/clean energy generation - key developments/requirements - technology gaps, components, systems,… - roadmap, technology, standards
	Organization:	- strawman plan, - next meeting, - potential role within IEEE
3:40-4:00	**Break**	
4:00-5pm	**6) Wrap-up Presentation and call for Consensus** **(Facilitator: Ron Wolk)**	
5pm	**Adjourn**	

Questions That We Hope Will Be Answered at this Workshop

Ron Wolk

April 8, 2008

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

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

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

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

5. What are the technology gaps?

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

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

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

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

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

11. What funding sources are available to support the achievement of these objectives?

High-Megawatt Power Converter Technology R&D Roadmap Workshop

Workshop Goals

Roadmap Vision; State-of-the-art grid connected inverter specifications, and goals, for future value added high-megawatt grid connected inverters

Why? Bigger Inverters, Faster Inverters, More and More Inverters ….

Leo Casey, VP & CTO
SatCon Technology Corporation
leo.casey@satcon.com

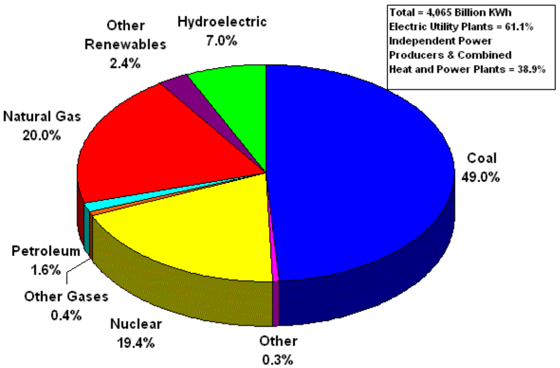


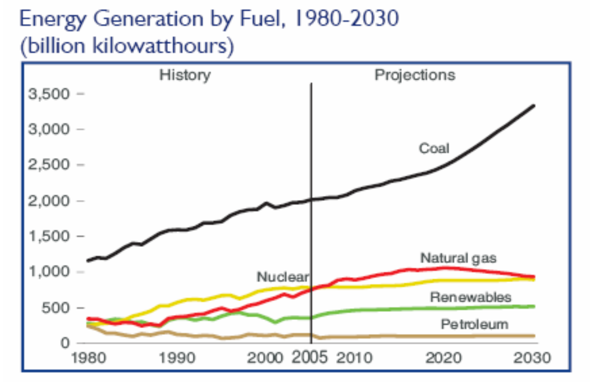


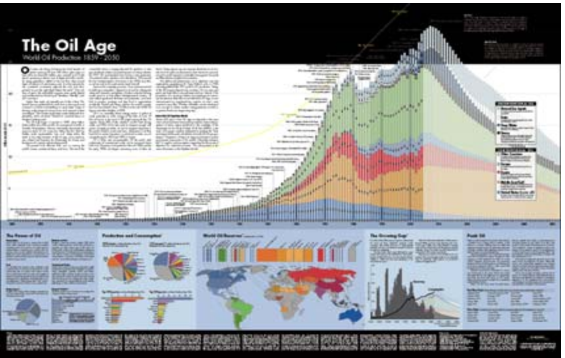



April 8, 2008

Environmental Factors and Increased Electrification







- Oil age is finite (cost, supply, security, environmental impact)
- Increasing Development
- Increasing Electrification

so renewables and Clean technologies

consider Wind

Cheap
Clean

Erratic/Unpredictable
Remote
Destabilizing
Low Utilization Factor

40% of US economy or 40Quads used to make 12.54Quads of Electricity in 2004 (100 Quads = 100 exajoule (100.10^{18}J))

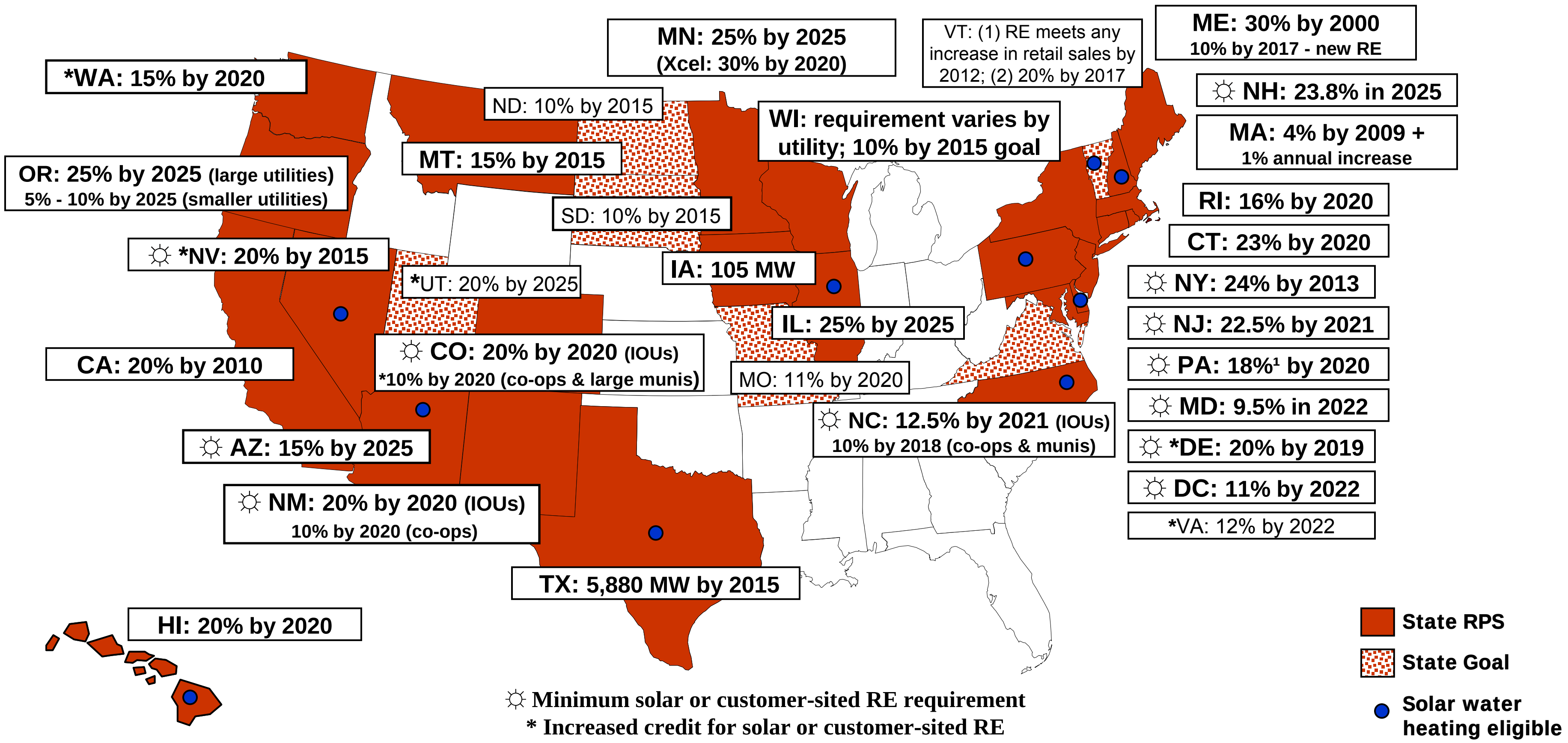
Storage is the obvious answer, Integrated Storage

RPS Requirements becoming the Driver Despite Uncertainty over ITCs

DSIRE: www.dsireusa.org

March 2008

Renewables Portfolio Standards



***WA: 15% by 2020**

OR: 25% by 2025 (large utilities)
5% - 10% by 2025 (smaller utilities)

☼ *NV: 20% by 2015

CA: 20% by 2010

☼ AZ: 15% by 2025

☼ NM: 20% by 2020 (IOUs)
10% by 2020 (co-ops)

HI: 20% by 2020

MT: 15% by 2015

ND: 10% by 2015

SD: 10% by 2015

*UT: 20% by 2025

☼ CO: 20% by 2020 (IOUs)
***10% by 2020 (co-ops & large munis)**

TX: 5,880 MW by 2015

MN: 25% by 2025
(Xcel: 30% by 2020)

IA: 105 MW

MO: 11% by 2020

IL: 25% by 2025

WI: requirement varies by utility; 10% by 2015 goal

☼ NC: 12.5% by 2021 (IOUs)
10% by 2018 (co-ops & munis)

VT: (1) RE meets any increase in retail sales by 2012; (2) 20% by 2017

ME: 30% by 2000
10% by 2017 - new RE

☼ NH: 23.8% in 2025

MA: 4% by 2009 +
1% annual increase

RI: 16% by 2020

CT: 23% by 2020

☼ NY: 24% by 2013

☼ NJ: 22.5% by 2021

☼ PA: 18%[1] by 2020

☼ MD: 9.5% in 2022

☼ *DE: 20% by 2019

☼ DC: 11% by 2022

*VA: 12% by 2022

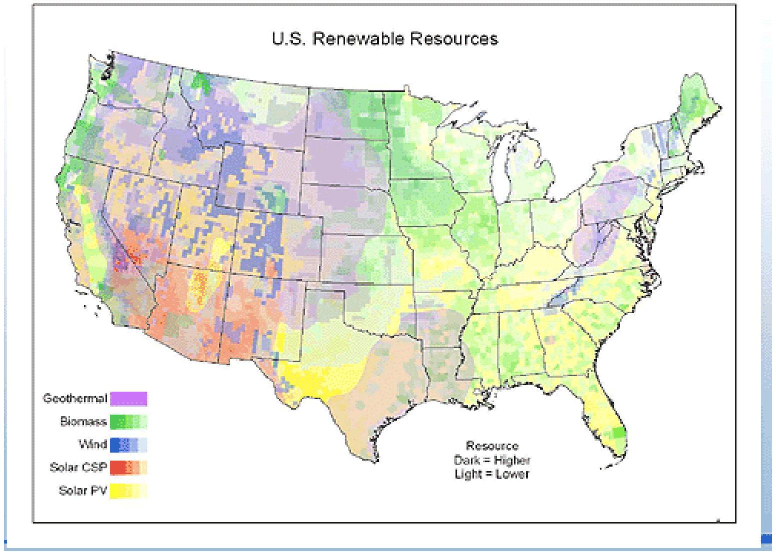
🟥 **State RPS**

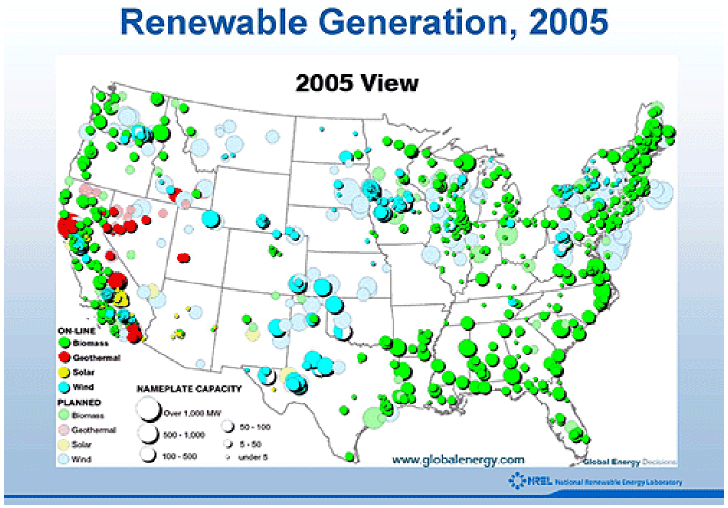
▨ **State Goal**

● **Solar water heating eligible**

☼ Minimum solar or customer-sited RE requirement
*** Increased credit for solar or customer-sited RE**
[1] PA: 8% Tier I / 10% Tier II (includes non-renewables)

Inverters Role in DER





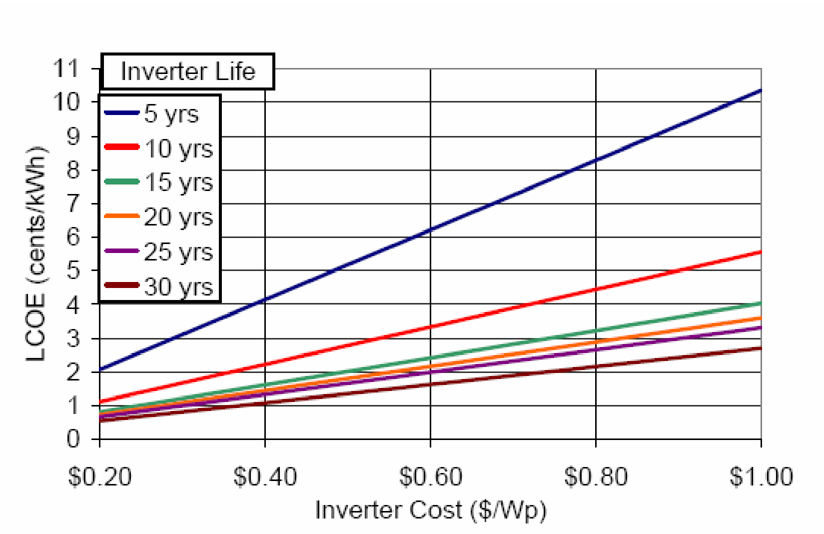
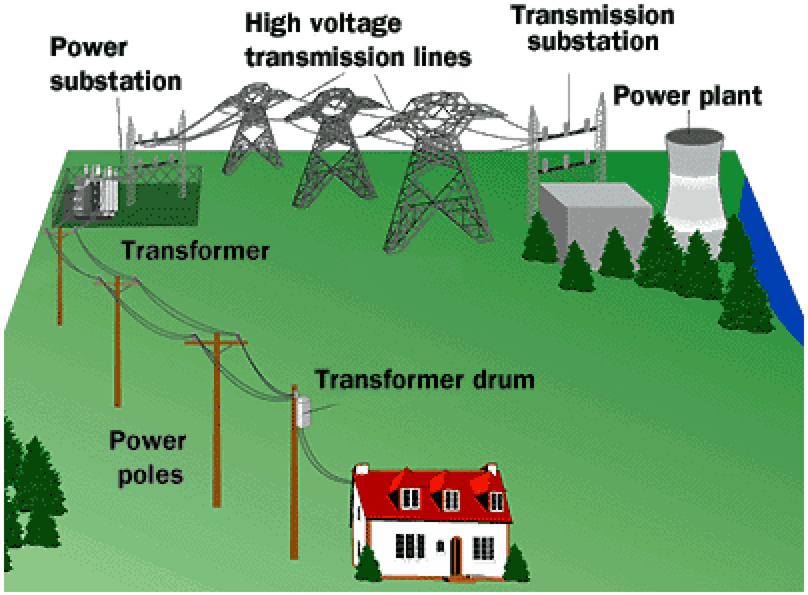


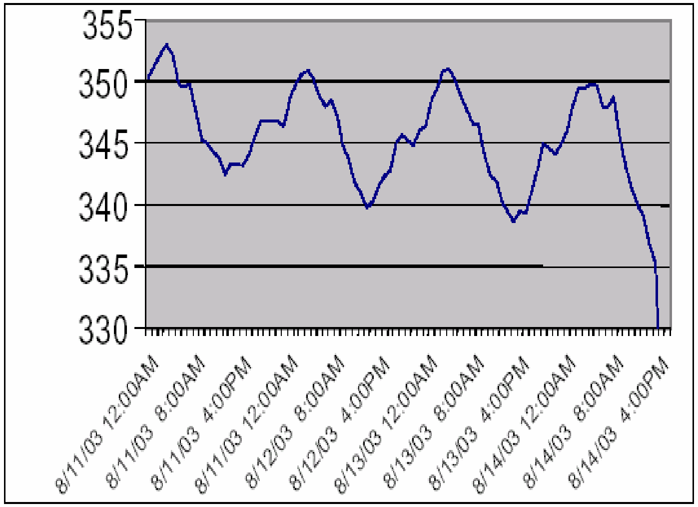
Figure 11. Contribution of Inverter Cost and Replacement to Energy Cost.

Primary Inverter Function and Focus

- Cost
- Reliability (10+ year warranties …)
- Availability (Reliability, MTTR, …)
- Efficiency
- Volume and Weight
- Other Performance metrics?

Why did the lights go out?
Isn’t this the age of the electron?





First Energy – Vegetation + Heat

- Grid is a beautiful thing
- Energy moves at the speed of light
- Rugged Electro-mechanical generators
- Spinning “reserve”
- Excess capacity (>15% is critical) **SIZED FOR**
- Low Impedance – typically 5% of rating at PCC
    - Fault clearance
    - Overload
- ac – Simple Impedance Transformation, and Isolation

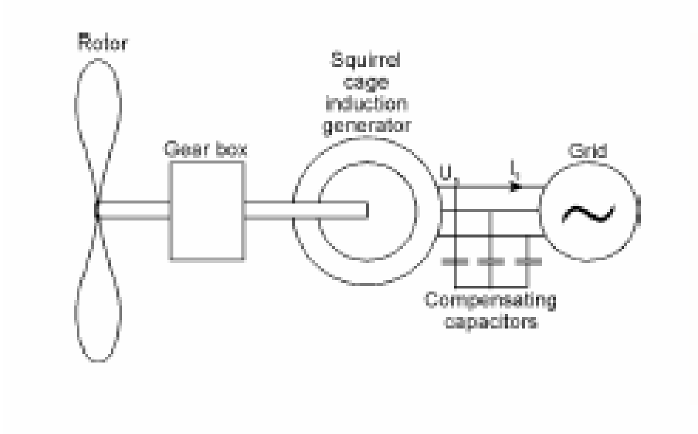
BUT, grid is,

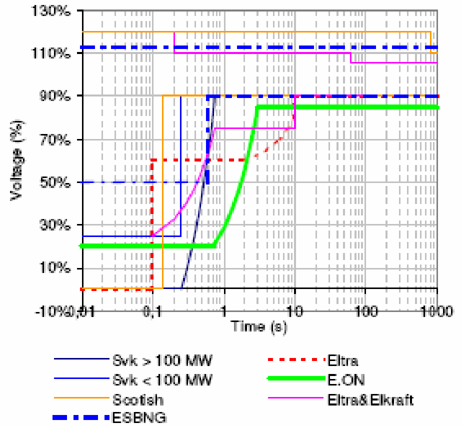
- **Slow**
    - **Response (Prime Movers, Controls)**
    - **Fault clearing, protection, coordination**
- **Smart Grid? Smart “slow” Grid still a slow grid. (load shedding is only relatively quick response)**

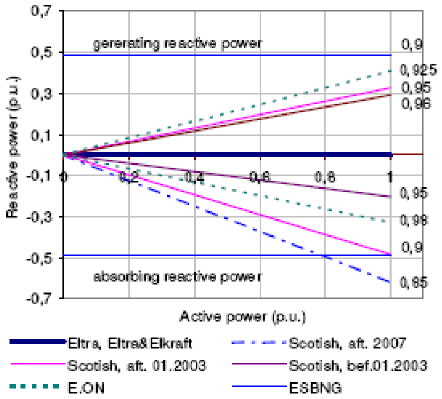
Grid Interconnection of DG

- Generators still most cost effective
- Power Electronic nature of Inverters brings great suspicion, (constant P characteristic, fast response,), hence some characteristics of regs (1547, …)
- Inverters can do much more that get the green e^-s on and off the grid. With storage can form microgrid, with control from utility can offer anciliary services, …
- Standards can inhibit technology (anti-islanding, tight trip points, … witness Wind and LVRT)

Wind -- Induction Generator Technology had poor PF and Ride-Thru







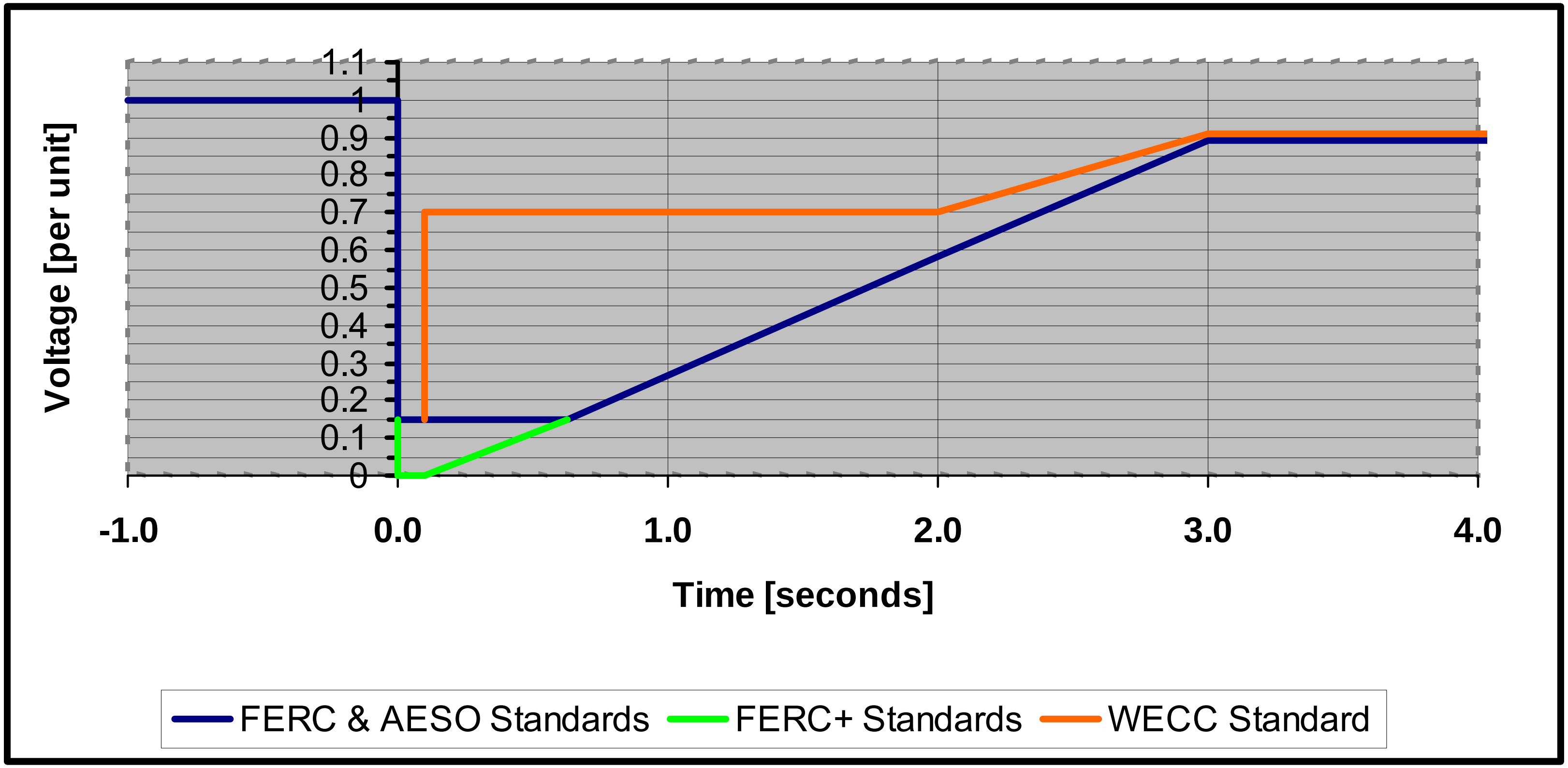
LV Ride-Through (LVRT) Requirement

- FERC, AESO, WECC Standards
- Substation LVRT Device / Equipment Solutions

Reactive Power Compensation Requirement

- FERC, AESO, Manitoba Hydro Standards
- Substation VAR Management Equipment Solutions

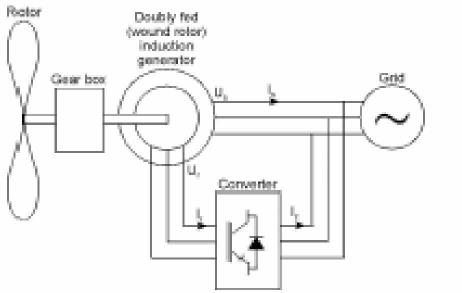
FERC, AESO, WECS LV "Ride-Through" Curves



Ride-Through – no trip

– synched?

– impedance?



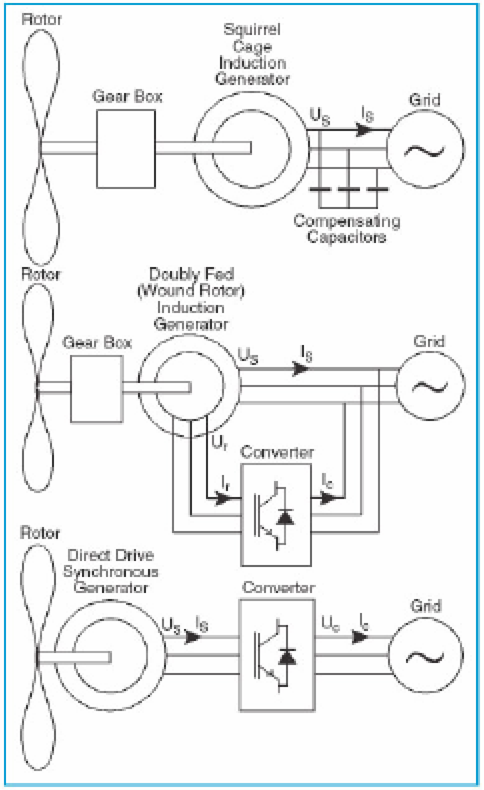
Doubly-Fed Machine can sink
or sources VARs, with high bandwidth control

Wind Generator and Power Backup / Storage Developments

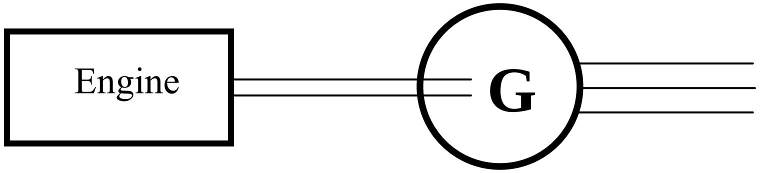
Past

Present

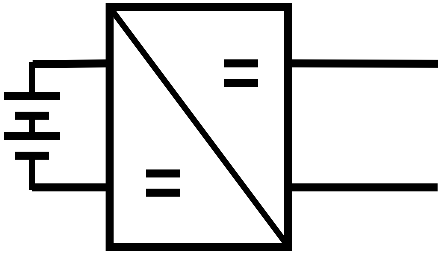
Future



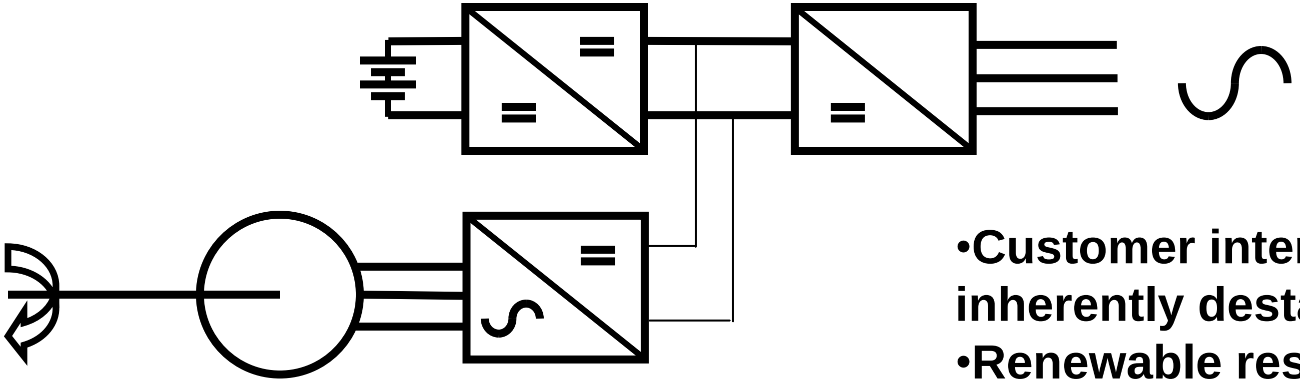
\+



\+



Fully Rated Inverter provides Many Possibilities



- Customer interface electronics, inherently destabilizing?
- Renewable resource potentially at odds with grid
- Or, can enhance, P, Q, dP/dt, nf, ABC
- Controllable (remotely)
- Supply Real Power, P
- Reactive power, Q, ($|P + jQ| < S_{INV}$)

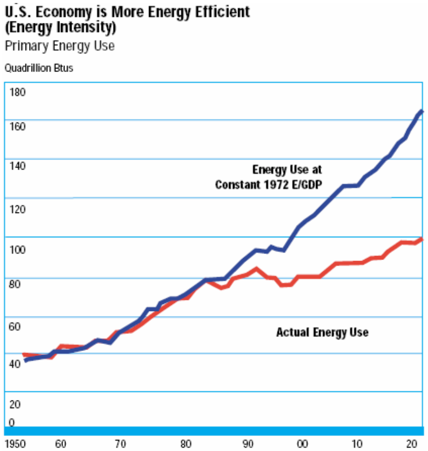
- Active Damping (stabilizing)
- Fault Clearing
- Rapid Dynamics
- Unbalanced, non-linear sourcing
- Active Filtering, harmonic cancellation
-
- NOT an Electrical Machine!!
-

Some Advanced Inverter Features

- Dispatchable Real Power
- Dispatchable Reactive Power (voltage support)
- Controllable Harmonic Cancellation
- Phase Balancing (imbalance)
- Controllable Inertia
- Controllable Trip Points
- Permissive Utility Controlled Islanding

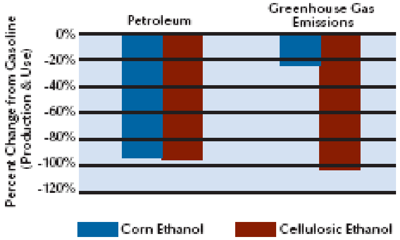
(Some) Grid Technology Developments

- Materials
  - Composites,
  - Super conductors?
- HVDC
- Devices
  - Silicon Carbide (devices + related)
    - solid state breakers
    - HV, HT Electronics
- Distributed sensing and control (smartgrid)
  - temp, volt, I,
- Communications
- Nuclear
- Demand side control
- Micro-grid (SDS + storage)
- Storage
- Efficiency (technology)?
- Improvements (FC, PV, Wind, ...)
- EV/HEV
- Biofuels, synthetic, cellulostic, ...
- Off-Shore Wind
- Storage, Storage, Storage, ...
- More Electronics, Faster, Better Control ...
- Higher Reliability Power Electronics
  - Prognostics



Improvements in energy efficiency since the 1970s have had a major impact in meeting national energy needs relative to new supply. If the intensity of U.S. energy use had remained constant since 1972, consumption would have been about 70 quadrillion Btus (74 percent) higher in 1999 than it actually was.

Source: U.S. Department of Energy, Energy Information Administration.



Data Source: Lynd, Greene, and Sheehan, 2004

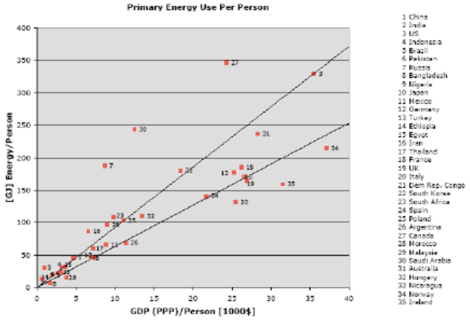


Figure 1.1 Energy use (in gigajoules) vs. GDP (on a purchasing power parity basis) for selected countries on a per capita basis. Data from the International Energy Agency. Upper line indicates ratio for the US; lower line indicates ratio for Japan and several Western European countries.

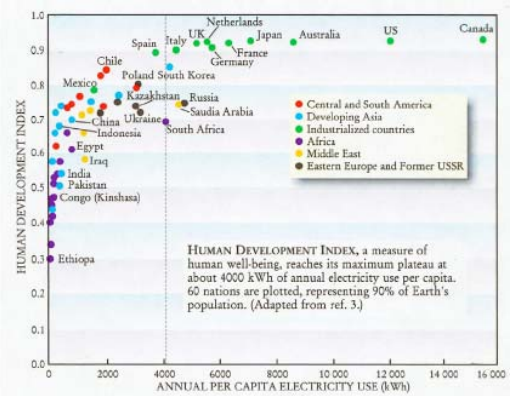
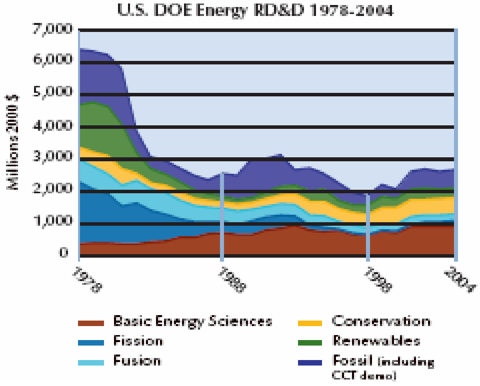


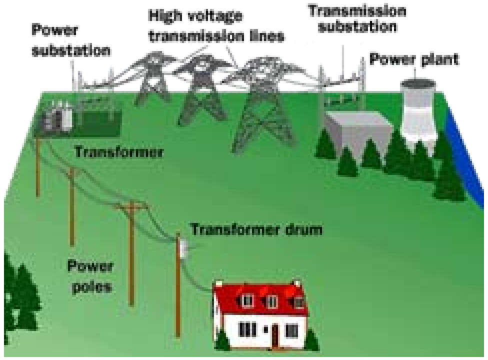
Figure 1.2. Human development index vs. per capita electricity use for selected countries. Taken from S. Benka, *Physics Today* (April 2002), pg 39, and adapted from A. Pasternak, Lawrence Liver



Power Distribution Options -- Battle

Thomas Edison and Joseph Swan

Pearl St, NY, 1882
Edison
85 Customers, 400 Lamps



Move it at HV

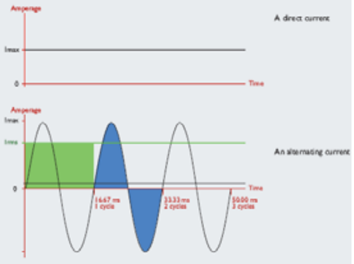
AC won (pre-electronics)
- **Transformer isolation**
- **Impedance (V) transformation**
- **Grounded Secondary (safety)**
- **AC → DC, easy**

$$d = \sqrt{\frac{2\rho}{\omega\mu}}$$

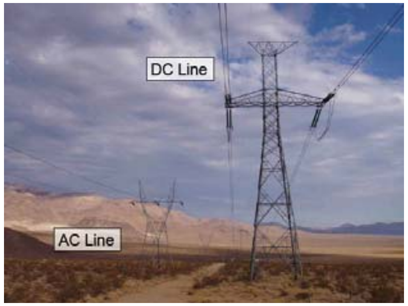
d or δ, 60Hz
Cu 8mm
Al 10mm
SiFe 0.1mm

But
- **Skindepth**
- **ϕ Imbalance**
- **Reactive power**
- **Peak to RMS**

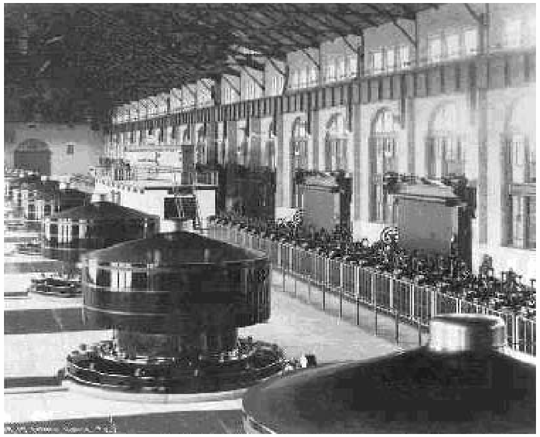
Edison was missing what?
Loads Today?
Sources Today
Storage?



Today, DC wins for T

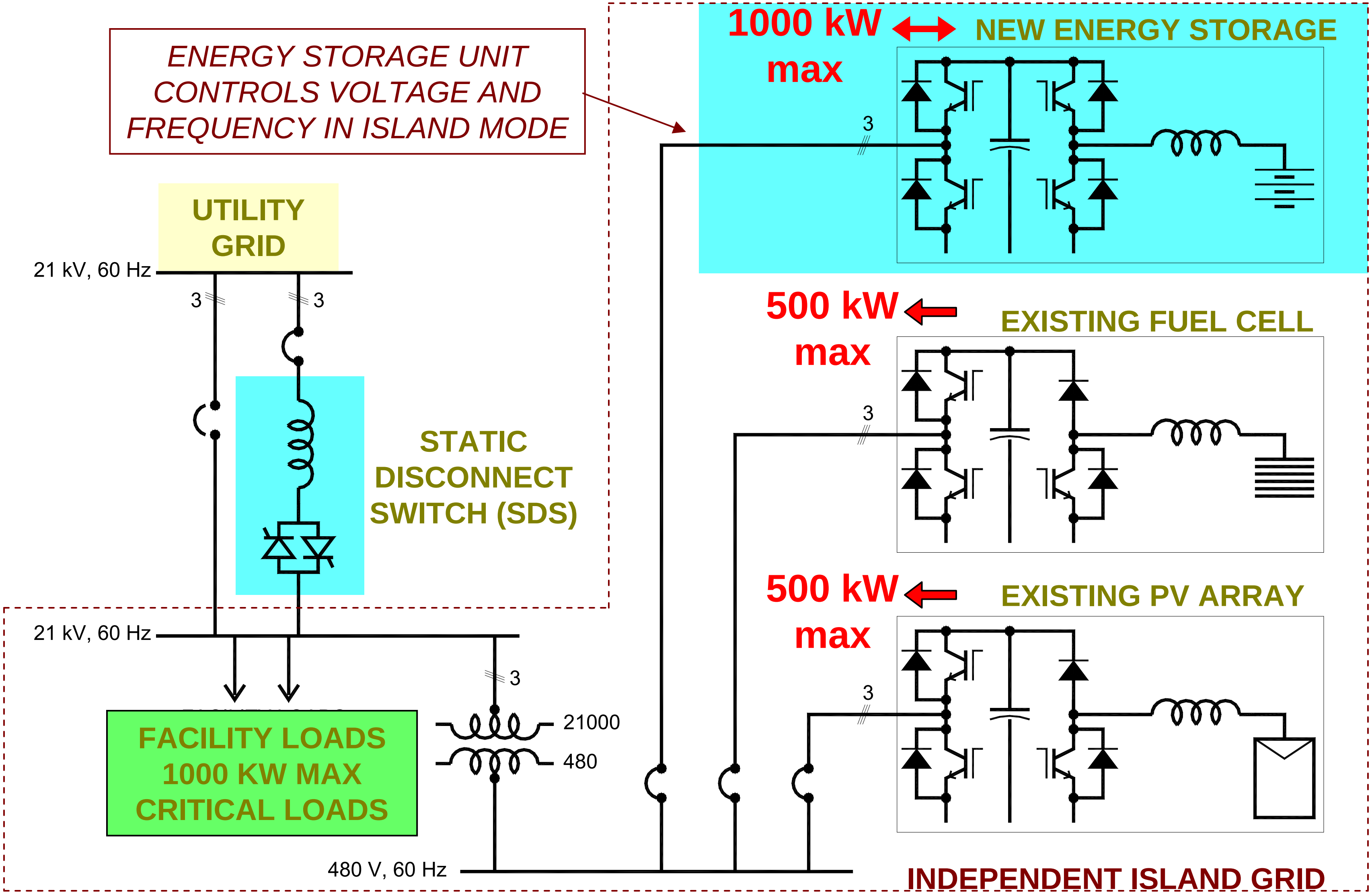


George Westinghouse and Nikola Tesla



Adams Hydroelectric Plant
Niagara Falls 1895
Westinghouse, Tesla, Stanley

Adding Energy Storage and a SDS Allows Existing DG Units to Support an Island Grid (μGrid)



ENERGY STORAGE UNIT CONTROLS VOLTAGE AND FREQUENCY IN ISLAND MODE

UTILITY GRID

STATIC DISCONNECT SWITCH (SDS)

FACILITY LOADS
1000 KW MAX
CRITICAL LOADS

1000 kW max ↔ NEW ENERGY STORAGE

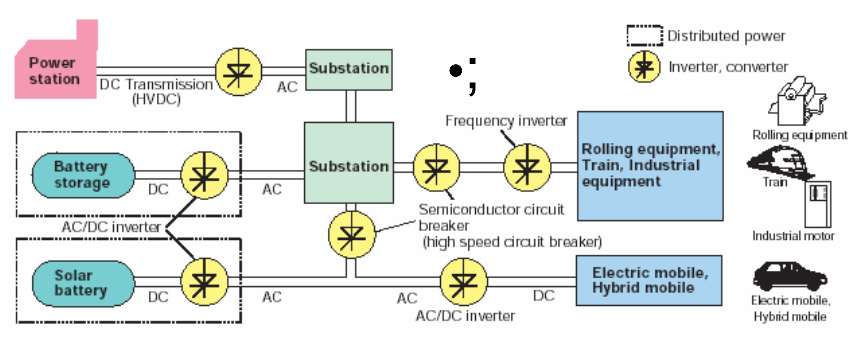
500 kW max ← EXISTING FUEL CELL

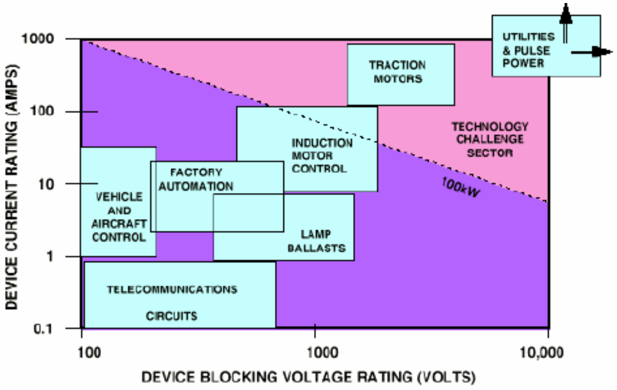
500 kW max ← EXISTING PV ARRAY

INDEPENDENT ISLAND GRID

Some Potential SiC (WBG) Impacts on Grids, Mini-Grids, Power Systems

- **Relaying** (electromechanical is 6-10 cycle, solid-state for LV, MV, HV)
  - Isolation (SSR)
  - Protection
  - Fault clearing
  - Fault limiting (SSCL)
- **Transmission Electronics** (MV, HV)
  - FACTS
  - VARS, (SVAR, DVAR)
  - DVR
  - STS
- **Grid electronics** (storage, renewables, PQ)
  - Volume
  - Weight
  - Efficiency
  - Reliability
  - Cost
  - Overload capability
  - Voltage/Power Application Range
- **Solid State Suppression**
  - Spikes
- **Solid State Transformers** (HF Link)





New Switch Capabilities enables new Applications

Hi-T, Hi-Rad, Hi-V, Hi-f

Big Inverters

- $200/KW? $100/KW?
- Extended Warranty? 10+ years
- Performance? 5KHz switching? 97%? 2sec overload?
- Research?
  - devices (SiC, GaN, … . Packaging, gate drives, control, passives, ….
  - Passives
  - STORAGE
  - Protection (relays, contactors)
  - Communication and Controls for Utility Inverters
  - Controls of Hybrid Power Systems and MicroGrids

SatCon Multi-Input, Single-Stage, 2.4 MW, 13.8 kV, Inverter

SOUTHERN CALIFORNIA
EDISON
An EDISON INTERNATIONAL℠ Company

Power, Energy & Grid Of the Future

SCE Distributed Energy Resources

April 8, 2008

High-Megawatt Power Converter Technology Roadmap Workshop

Power, Energy & Grid Of the Future – Presentation Overview

- SCE DER Activity
- Inverter Interface – What Do I Want
- Beyond DER Activity

SCE DER Activity

- Prime Mover - MTG Generator Testing
- **Grid Interface** – Interconnection Criteria, Advanced Inverter Development Input ‘Utility Perspective’
- Advanced Operating Concepts – Microgrids, DER as System Asset, Smart Grid

SCE DER Activity – Grid Interface

- IEEE Draft Std 1547.4, Intentional DG Islands
  - A KEY SCE PARTICIPATION DRIVER: Concepts Relevant to Accomplishing *Feasible* High Renewable Penetration
  - DoE OE RDSI Proposal ‘Catalina Renewable DG’: Demonstration of High Renewable Penetration
- 20% BY 2010 California’s Renewable Portfolio Standard
  - 20% renewables with significant intermittent content will require more than ‘business as usual’
    - 4,000 MW Wind
    - 1,000 MW Solar
  - Energy Storage *with Advanced PCS*, A Solution?

Inverter Interface – What Do I Want

- Starting Point - Do No Harm. Safety first. Mission accomplished…but…

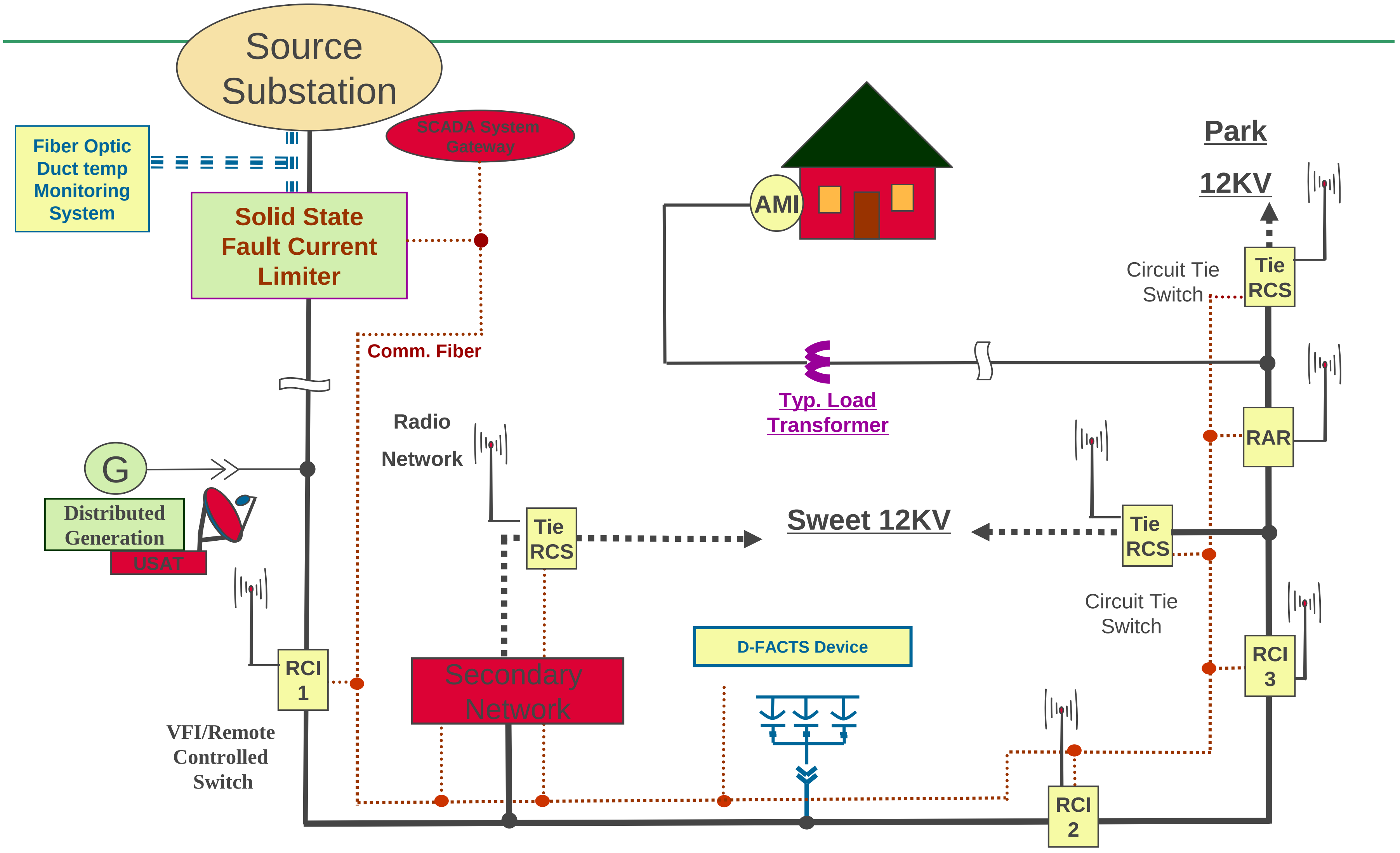
- Moving Toward - System Support from DER. High renewable penetration, grid reliability support, grid-side power quality support

- Inverter Needs - Magnitude, Grid Interactive, Reliable, Cost Competitive, Innovation Incentive Rate

Beyond DER Activity

- SCE’s Circuit of the Future D-FACTS: “What and Why”
- Phasor Measurement Unit (PMU) Application Development: PMU Assisted System Restoration
- Advanced Energy Storage for Wind Integration
- SCE 250 MW PV Project: Interface Specification

SCE's Circuit of the Future



Source Substation

SCADA System Gateway

Fiber Optic Duct temp Monitoring System

Solid State Fault Current Limiter

Comm. Fiber

AMI

Park 12KV

Circuit Tie Switch

Tie RCS

Typ. Load Transformer

RAR

Radio Network

G

Distributed Generation

USAT

Tie RCS

Sweet 12KV

Tie RCS

Circuit Tie Switch

D-FACTS Device

Secondary Network

RCI 1

VFI/Remote Controlled Switch

RCI 3

RCI 2

SCE’s Circuit of the Future
D-FACTS

D-SVC Performance Specification, Overview

WHAT DO WE WANT?

- Fast response and mitigation of temporary voltage sags
  - Respond and mitigate infrequent temporary deep sags -7 to -12%, (15/year recorded, EPRI DPQ Study)
  - Don’t try to fix very infrequent serious events: block device if sag exceeds -12% (Rule 21-based limit)

INPUT FOR DEVELOPMENT OF SPECIFICATION:

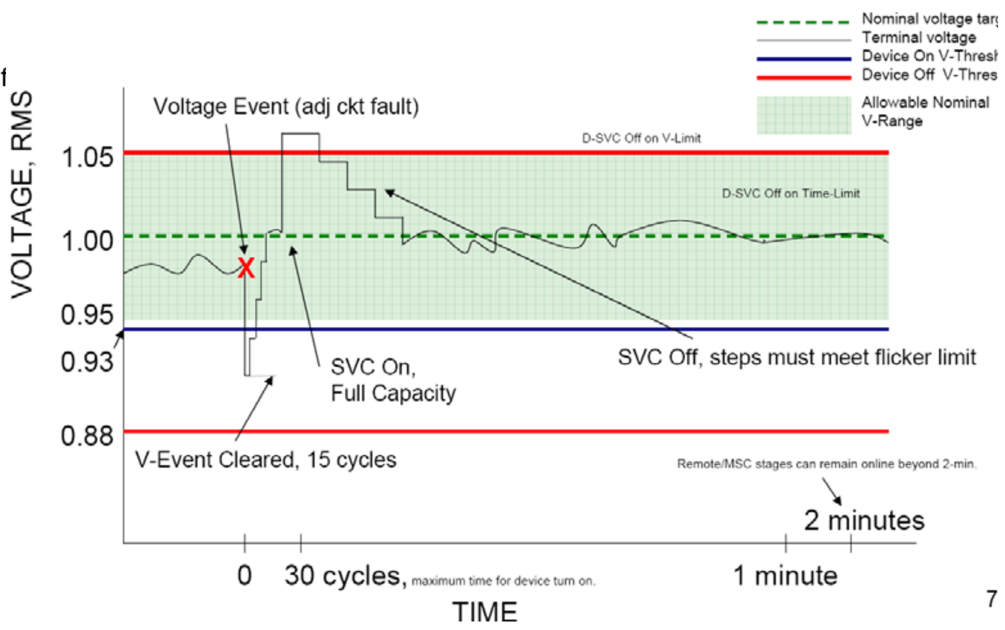
- Emulate organization/headings from relevant sections of I
  - “Existing Power System Characteristics” (3.8)
  - “Electrical Performance Requirements” (3.9)
  - “SVC Operating Characteristics” (3.10)

  But, much less detail needed. And, distribution vs. transmission f IEEE PQ Std vs. WECC T-Planning Criteria.

<u>All stated quantities</u> for proposed D-SVC spec refer to or are relevant to distribution:

  - SCE CPUC Tariff Rule 2
  - SCE Voltage Fluctuation Limit Criteria
  - IEEE 1559 PQ Monitoring Standard
  - IEEE 519 Harmonic Limits

D-SVC Operation Illustration, Cleared Fault Voltage & Time Thresholds



PMU Assisted System Restoration

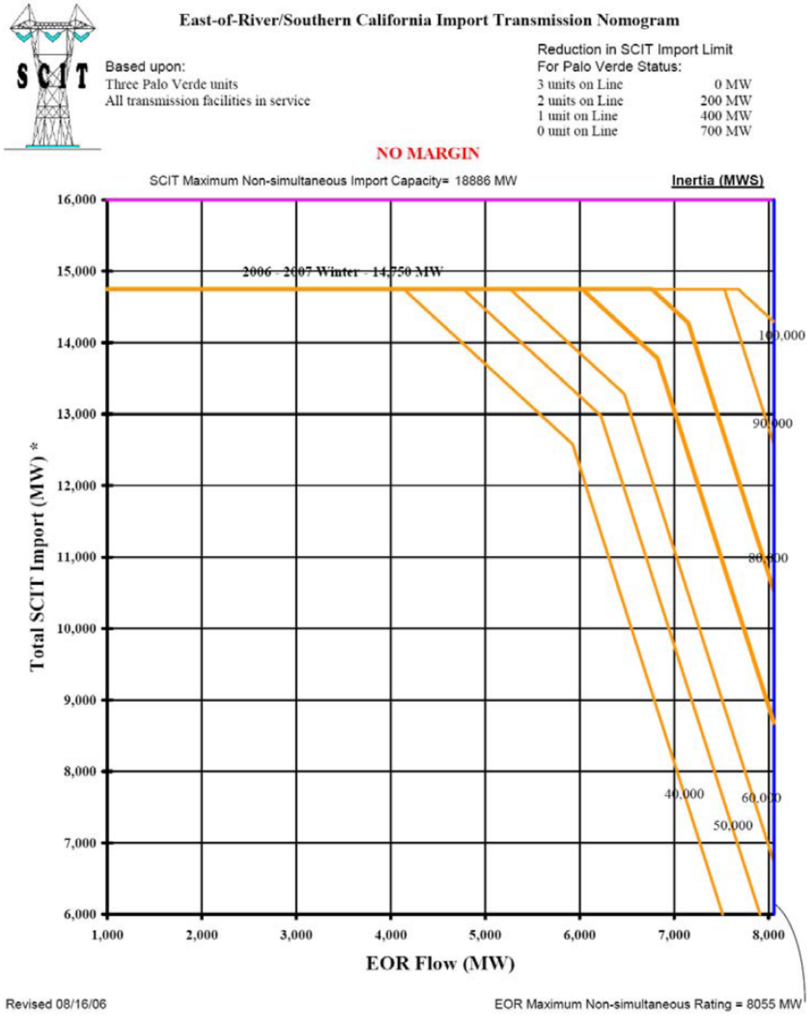
Energy Storage System Impact

Mega

Storage

O.C

- SCIT NOMOGRAM
  - Dynamic Stability and Transient Voltage Constrained
  - Constraint Based on Total MW-S Inertia in So Cal Load Center
  - RELIABILITY, AND COMMERCIAL, IMPLICATIONS



. BC

R

V

. M

A

V

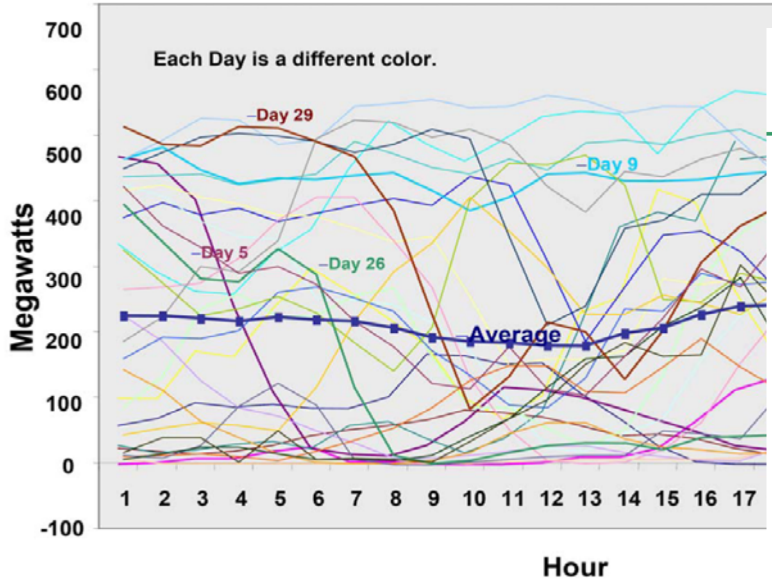
L

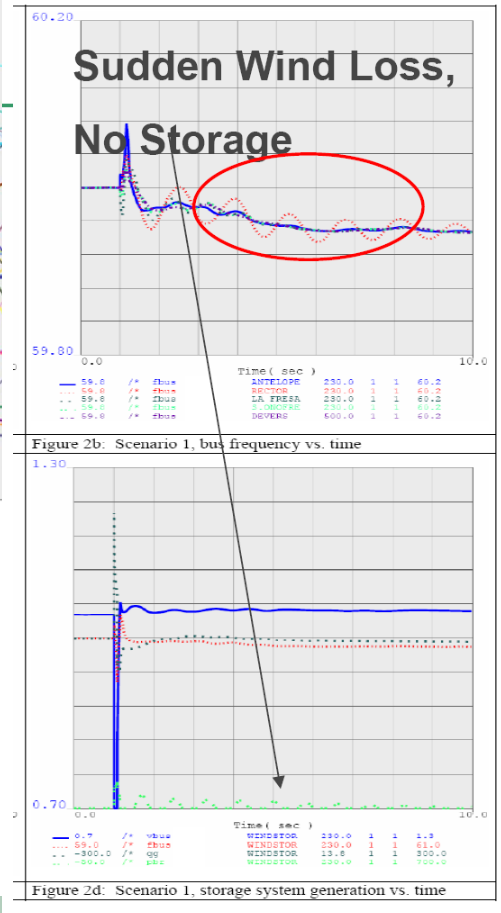
. S

Advanced Energy Storage for Wind Integration

- Operating the CAISO system with 20% Renewables - 6700 MW of wind presents significant challenges

Tehachapi – April 2005





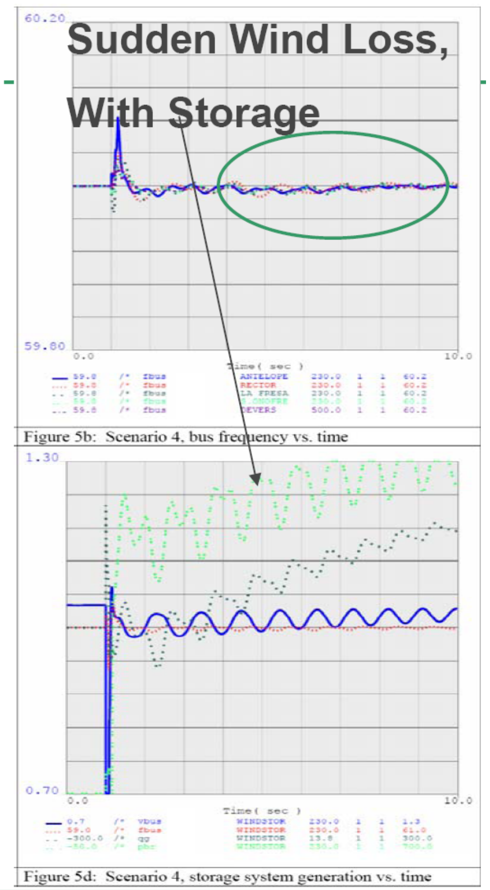
Sudden Wind Loss,

No Storage

Figure 2b: Scenario 1, bus frequency vs. time

Figure 2d: Scenario 1, storage system generation vs. time

try, March 2008 FINAL DRAFT FOR REVIEW



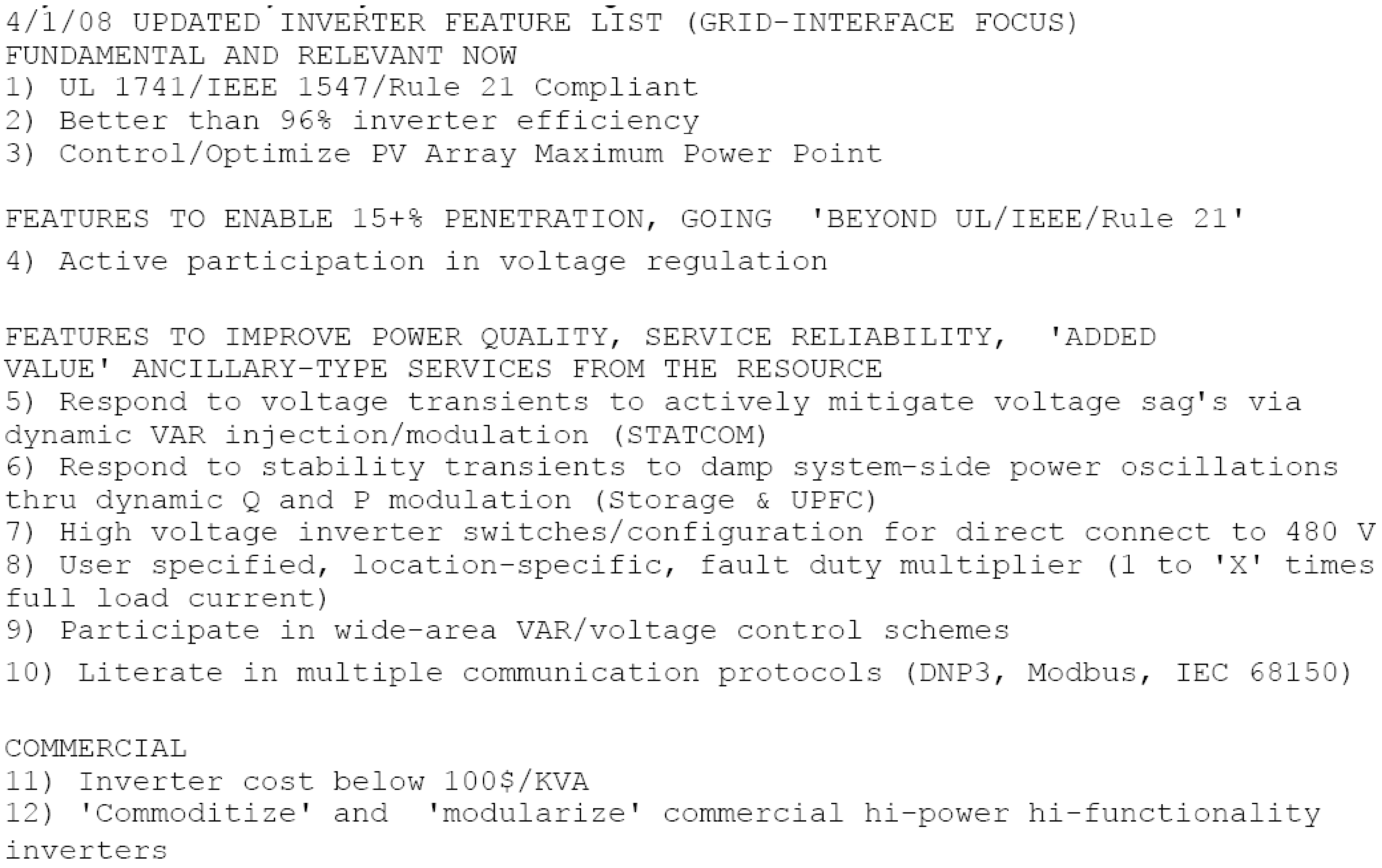
Sudden Wind Loss,

With Storage

Figure 5b: Scenario 4, bus frequency vs. time

Figure 5d: Scenario 4, storage system generation vs. time

Inverter Interface – Early Feature List for SCE's 250 MW PV Project



4/1/08 UPDATED INVERTER FEATURE LIST (GRID-INTERFACE FOCUS)

FUNDAMENTAL AND RELEVANT NOW

1) UL 1741/IEEE 1547/Rule 21 Compliant

2) Better than 96% inverter efficiency

3) Control/Optimize PV Array Maximum Power Point

FEATURES TO ENABLE 15+% PENETRATION, GOING 'BEYOND UL/IEEE/Rule 21'

4) Active participation in voltage regulation

FEATURES TO IMPROVE POWER QUALITY, SERVICE RELIABILITY, 'ADDED VALUE' ANCILLARY-TYPE SERVICES FROM THE RESOURCE

5) Respond to voltage transients to actively mitigate voltage sag's via dynamic VAR injection/modulation (STATCOM)

6) Respond to stability transients to damp system-side power oscillations thru dynamic Q and P modulation (Storage & UPFC)

7) High voltage inverter switches/configuration for direct connect to 480 V

8) User specified, location-specific, fault duty multiplier (1 to 'X' times full load current)

9) Participate in wide-area VAR/voltage control schemes

10) Literate in multiple communication protocols (DNP3, Modbus, IEC 68150)

COMMERCIAL

11) Inverter cost below 100$/KVA

12) 'Commoditize' and 'modularize' commercial hi-power hi-functionality inverters

SCE’s 250 MW PV Project

- Filed w/ CPUC, Ratebase 250 MW PV, $875 Million
- 50 MW/year, 5 Years
- 2 MW Pilot Project, In Service August 2008
- 1-2 MW Increments
- 3.5 $/Watt
- Connect on grid-side at 12 kV
- Non-utility roof space, equipment suppliers, installers, O&M services
- Support CA Solar Initiative targets. Of 805 MW available in SCE’s service territory only about 50 MW deployed. Average CSI installed cost for residential over $8/Watt

TRANSFORMING THE ELECTRIC GRID: A ROLE FOR HMW INVERTERS

April 2008

Alex M. Stanković
Northeastern University, Boston
`astankov@ece.neu.edu`

Presentation Map

- Energy Systems - Past & Present
- Energy Systems - Future,

Why Energy Systems?

Systems aim to achieve level reliability that far exceeds the reliability of individual components, through corrections of control actions based on evaluating or sensing its current state.

Why Energy Systems?

Systems aim to achieve level reliability that far exceeds the reliability of individual components, through corrections of control actions based on evaluating or sensing its current state.

Examples of energy system reliability targets:

Reliability %	N "nines"	Down time
99.9	3	9 hr/yr
99.999	5	5 min/yr
99.99999	7	3 sec/yr
99.9999999	9	2 cycles/yr

Why Energy Systems?

Systems aim to achieve level reliability that far exceeds the reliability of individual components, through corrections of control actions based on evaluating or sensing its current state.

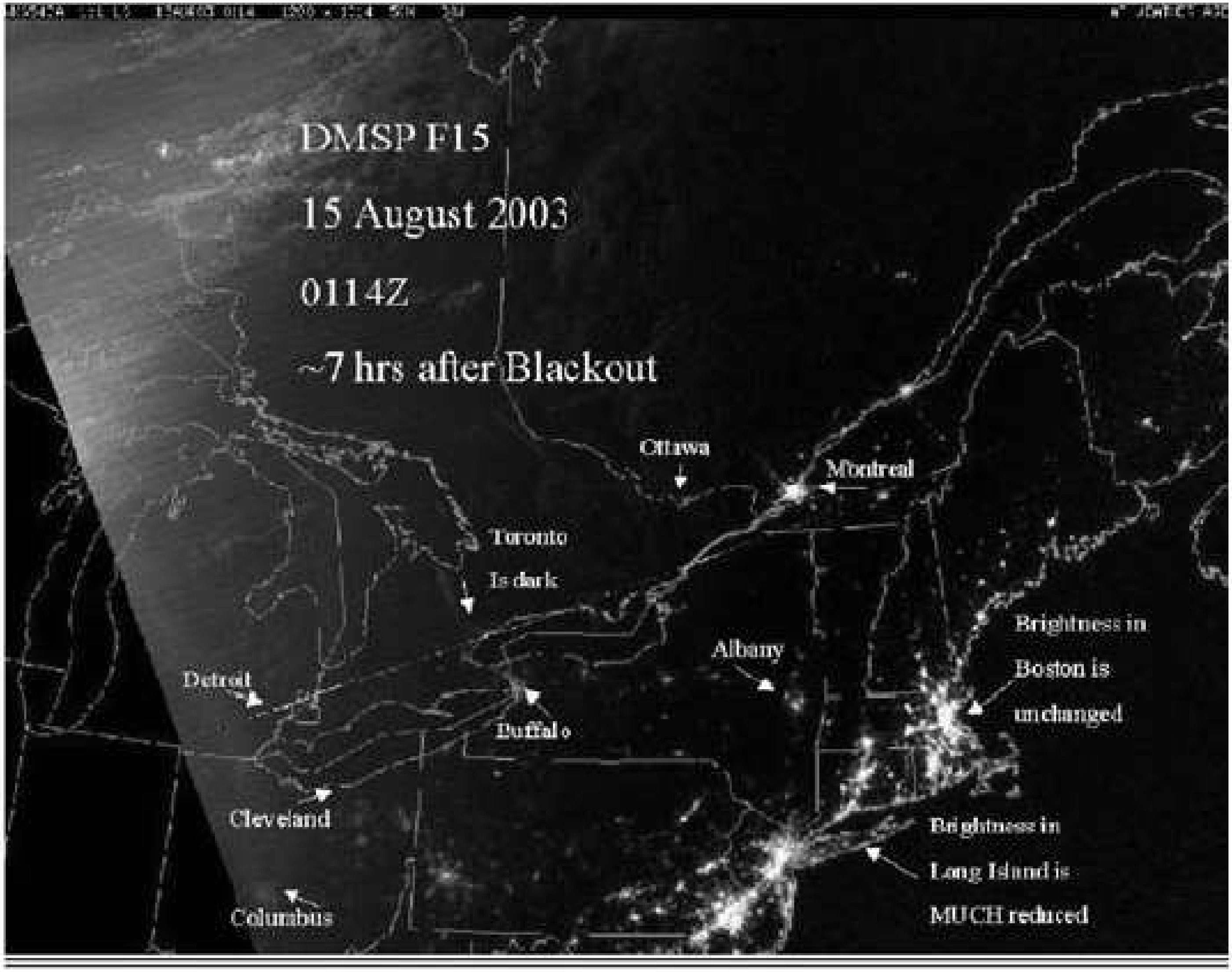
Examples of energy system reliability targets:

Reliability %	N "nines"	Down time
99.9	3	9 hr/yr
99.999	5	5 min/yr
99.99999	7	3 sec/yr
99.9999999	9	2 cycles/yr

Events from real life (G.T. Heydt):

Losing in roulette	N=1.6
Losing the PowerBall lottery	N=6
FAA design for aircraft	N=9-12

Cascading Faults



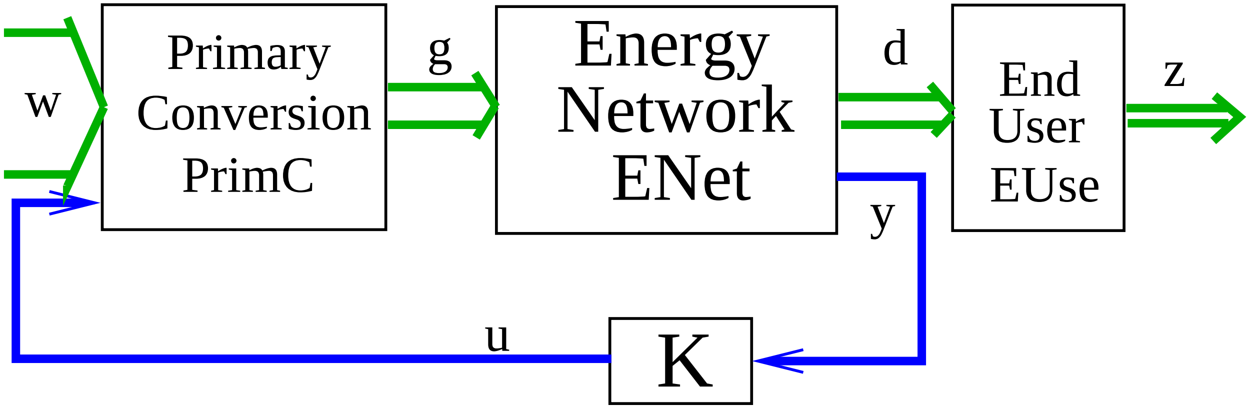
Characteristics of Energy Networks

- Built for efficiency.
- Multi-scale in time (>10 orders of magnitude), space (>7 orders of magnitude) and by power flow (>10 orders of magnitude).
- Hybrid - continuous and discrete acting components.
- Normal and faulted operation (nature and human adversaries).

Characteristics of Energy Networks

- Built for efficiency.
- Multi-scale in time (>10 orders of magnitude), space (>7 orders of magnitude) and by power flow (>10 orders of magnitude).
- Hybrid - continuous and discrete acting components.
- Normal and faulted operation (nature and human adversaries).
- Two main layers - energy and information flow.
- Limited actuation.
- Uncertainty (epistemic and aleatory).
- Input/Output characteristics are regularized by physics (conservation laws, coherences and invariants).

Existing Energy Systems



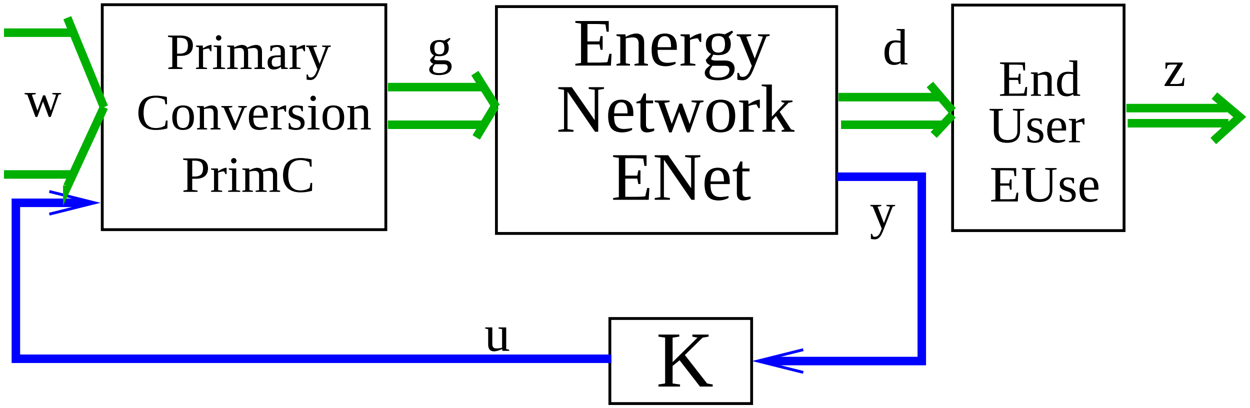
Primary Conversion PrimC

Energy Network ENet

End User EUse

K

Existing Energy Systems



- **w** too large, little from renewables,
- Unable to integrate novel components,
- Non-functional markets,
- Over-designed components - variations in **z**,
- Over-designed components - fault accommodation,
- Cascading faults.

Existing Energy Systems - Technical

- Not enough adaptation due to the insufficient information layer - control is too local, sometimes myopic,
- Significant variations in the part of $\mathbf{w}$ from renewables - large bandwidth and stochastic nature,
- No storage - a slow system is tracking variable $\mathbf{z}$,
- Large variations in $\mathbf{z}$ (and $\mathbf{w}$) - cyclic and stochastic,
- Individual blocks have substantial loses,

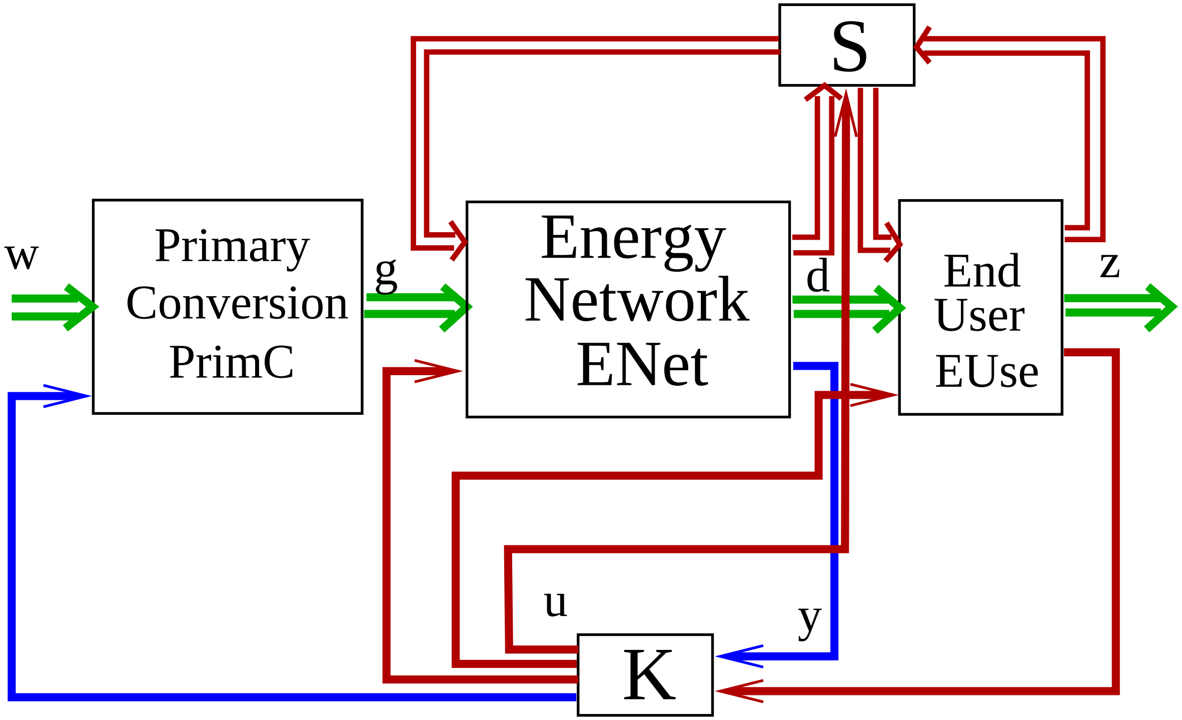
Existing Energy Systems - Technical

- Not enough adaptation due to the insufficient information layer - control is too local, sometimes myopic,
- Significant variations in the part of $\mathbf{w}$ from renewables - large bandwidth and stochastic nature,
- No storage - a slow system is tracking variable $\mathbf{z}$,
- Large variations in $\mathbf{z}$ (and $\mathbf{w}$) - cyclic and stochastic,
- Individual blocks have substantial loses,
- The inflexible overall architecture sometimes results in complex behavior - the system is very large, and the control authority is limited,
- Legacy components stifle innovation.
- Fault accommodation in slow hardware.

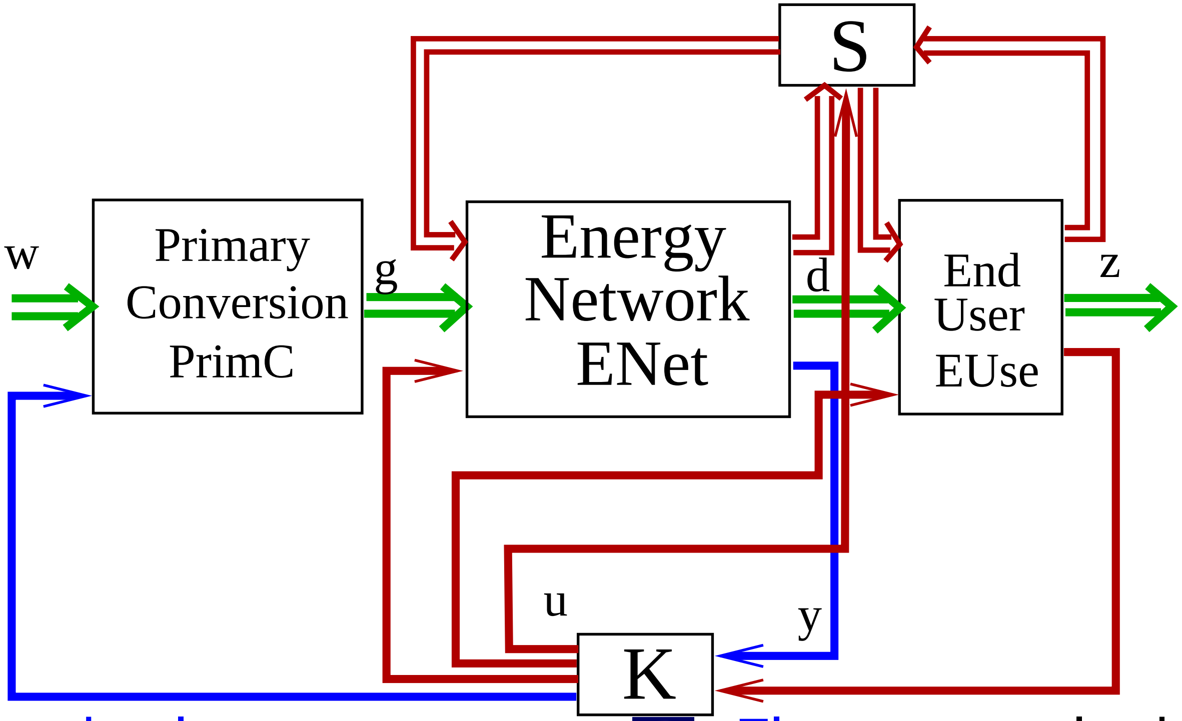
Presentation Map

- Energy Systems - Past & Present
- Energy Systems - Future,

Future Energy Systems VLSIE



Future Energy Systems VLSIE



- Information layer (sensors, coordinated K = local + global context, loads inside)
- Better blocks,
- More **w** from renewables,
- Flatter control - decoupling from above and below, faster, more authority via storage and routing,
- Better design while steering component development.

A Role for HMW Inverters

HMW inverters are a key enabling technology:

- A network with controlled flows (cf. free-flow today),
- Accommodate faults faster (before thermal, mechanical and chemical aspects start to dominate the design),
- Enable energy storage (especially large and fast),
- Enable better control - decompose the network to smaller, manageable pieces.

Getting there...

- Progress of technology in energy systems - “like visiting a graveyard in the company of Nietzsche” - Willems,

Getting there...

- Progress of technology in energy systems - “like visiting a graveyard in the company of Nietzsche” - Willems,
- Society expects 1) carbon-free electricity, 2) networks resilient to outages, and 3) functional markets and public policy.

Getting there...

- Progress of technology in energy systems - “like visiting a graveyard in the company of Nietzsche” - Willems,
- Society expects 1) carbon-free electricity, 2) networks resilient to outages, and 3) functional markets and public policy.

Transition:

- The efficiency is determined by the energy flow layer,
- Key enablers for improvement are in the information flow layer,
- The trajectory to future energy systems will be economy and policy driven (e.g., energy levels for sensors vs. storage).

Getting there...

- Progress of technology in energy systems - “like visiting a graveyard in the company of Nietzsche” - Willems,
- Society expects 1) carbon-free electricity, 2) networks resilient to outages, and 3) functional markets and public policy.

Transition:

- The efficiency is determined by the energy flow layer,
- Key enablers for improvement are in the information flow layer,
- The trajectory to future energy systems will be economy and policy driven (e.g., energy levels for sensors vs. storage).
- “The energy crisis appears to me to be more a crisis of momentum than of energy – a crisis of enterprise, solidarity, common spirit, determination and cooperation for the common good.” - Ulam

ACKNOWLEDGMENTS

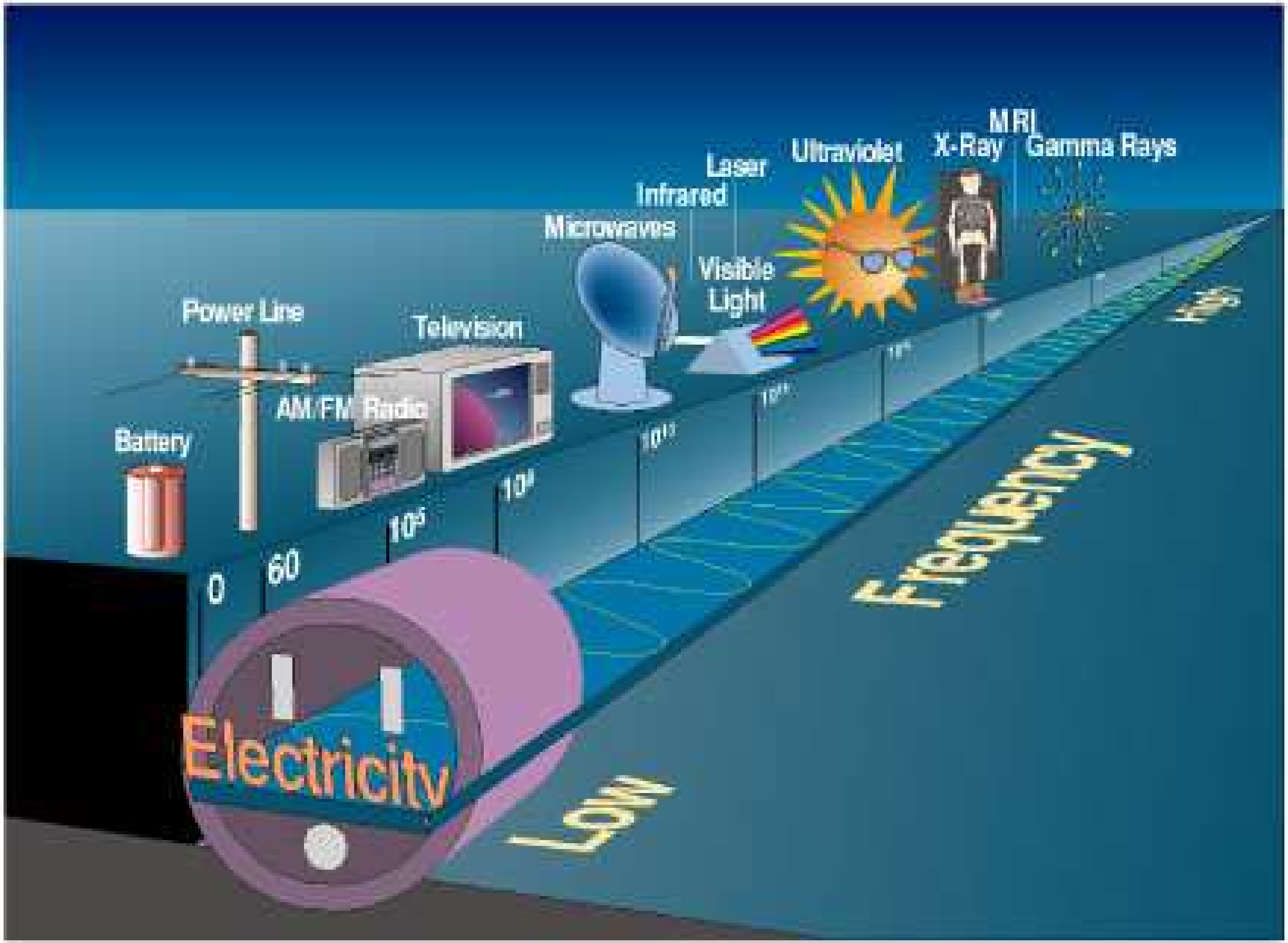
My heartfelt thanks to many colleagues and former students consulted about energy systems: M. Amin, G. Andersson, T. Aydin, M. Begovic, D. Boroyevich, C. DeMarco, I. Dobson, G. Escobar, J. Hauer, D. Hill, M. Ilic, C. Jacobson, I. Kamwa, J. Kolar, P. Kokotovic, B. Krogh, J. Lang, H. Lev-Ari, P.-A. Lof, N. Martins, P. Mattavelli, M. Morari, M.A. Pai, M. Perisic, R. Ortega, N. Rau, J. Sanchez-Gasca, A. Saric, P. Sauer, S. Sanders, A. Sangiovanni-Vincentelli, D. Siljak, C. Taylor, G. Verghese, F. Wu.

Contact info:

astankov@ece.neu.edu
www.ece.neu.edu/faculty/stankovic

Future...

A new positioning of energy processing within EE (C. Gellings):



NAE Grand Challenges

14 grand challenges for engineering in the 21-st century (Feb. 2008):

- 1. Environmentally friendly power.
- 2. Nuclear fusion.
- 3. Carbon dioxide sequestration.
- 6. Sustaining the aging infrastructure.

NAE Grand Challenges

14 grand challenges for engineering in the 21-st century (Feb. 2008):

- 1. Environmentally friendly power.
- 2. Nuclear fusion.
- 3. Carbon dioxide sequestration.
- 6. Sustaining the aging infrastructure.

A recurring theme: “The vast networks of electrification are the greatest engineering achievement of the 20-th century.”

Grand Challenges in Energy Engineering

IEEE Power Engineering Society, 2002:

- 1. Total control of power flow in networked systems.
- 2. Self-healing networks to achieve zero outages.
- 3. Zero-error state estimation.
- 10. Real time dynamic simulation of a 50 000 node, 2 000 generator, 500 000 MW system.

FLORIDA SOLAR ENERGY CENTER

Creating Energy Independence Since 1975

Utility Needs of Power Conditioning Systems for PV and other Renewable DG

A New Twist

Bob Reedy
+1.321.638.1470
reedy@fsec.ucf.edu

A Research Institute of the University of Central Florida

“Green Power” ??

Keep in Mind – Fundamentals of Electricity Transmission

Thermal Limits on Lines

Keep in Mind – Fundamentals of Electricity Transmission

Power Transfer Limits

Keep in Mind – Fundamentals of Electricity Transmission

Voltage, Current, Frequency and Power

Keep in Mind – Fundamentals of Electricity Transmission

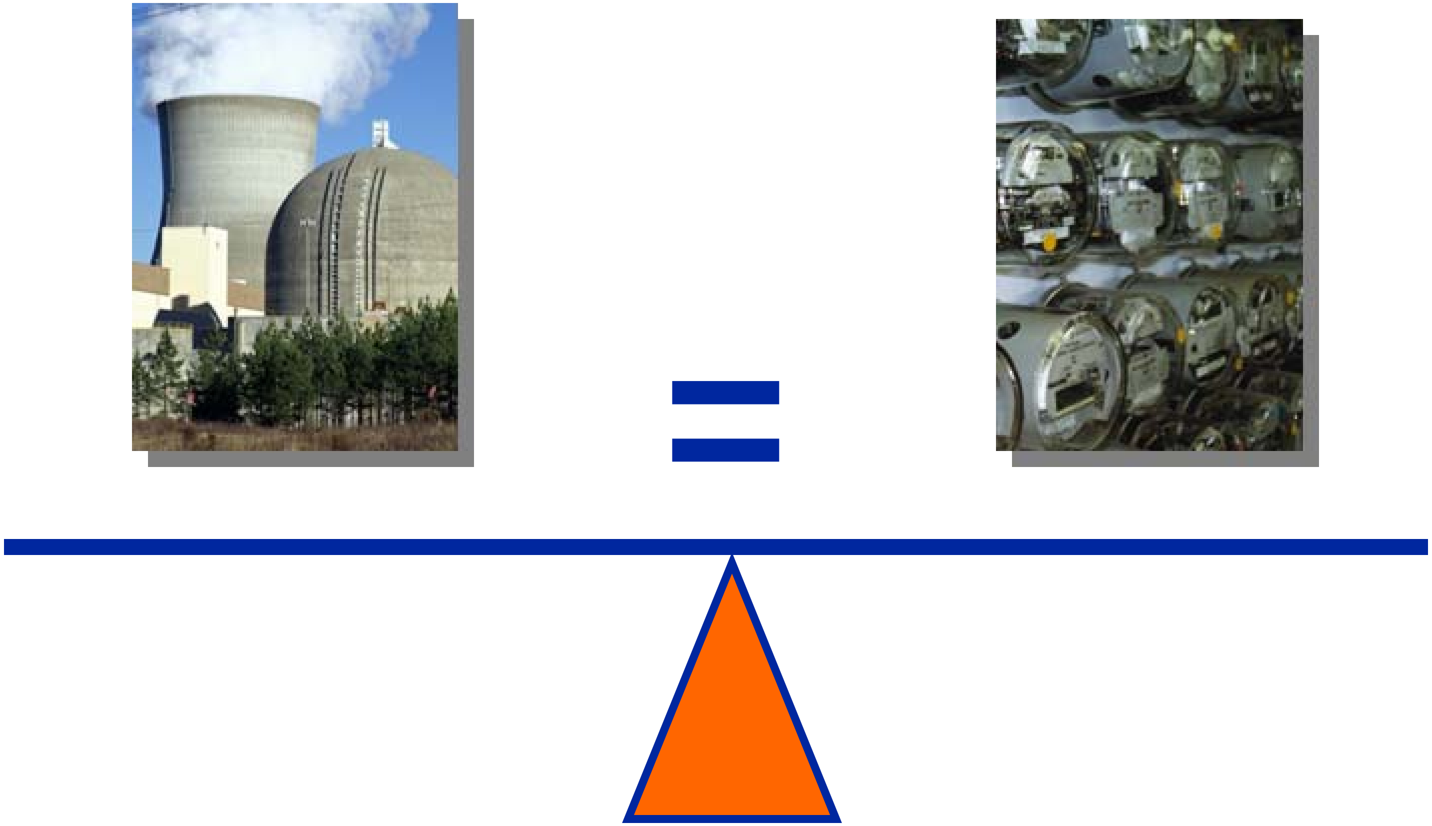
Complex Enough in Steady State, System Disturbances are Difficult to Predict

Keep in Mind – Fundamentals of Electricity Transmission

When Things “Trip”, it can get Crazy !

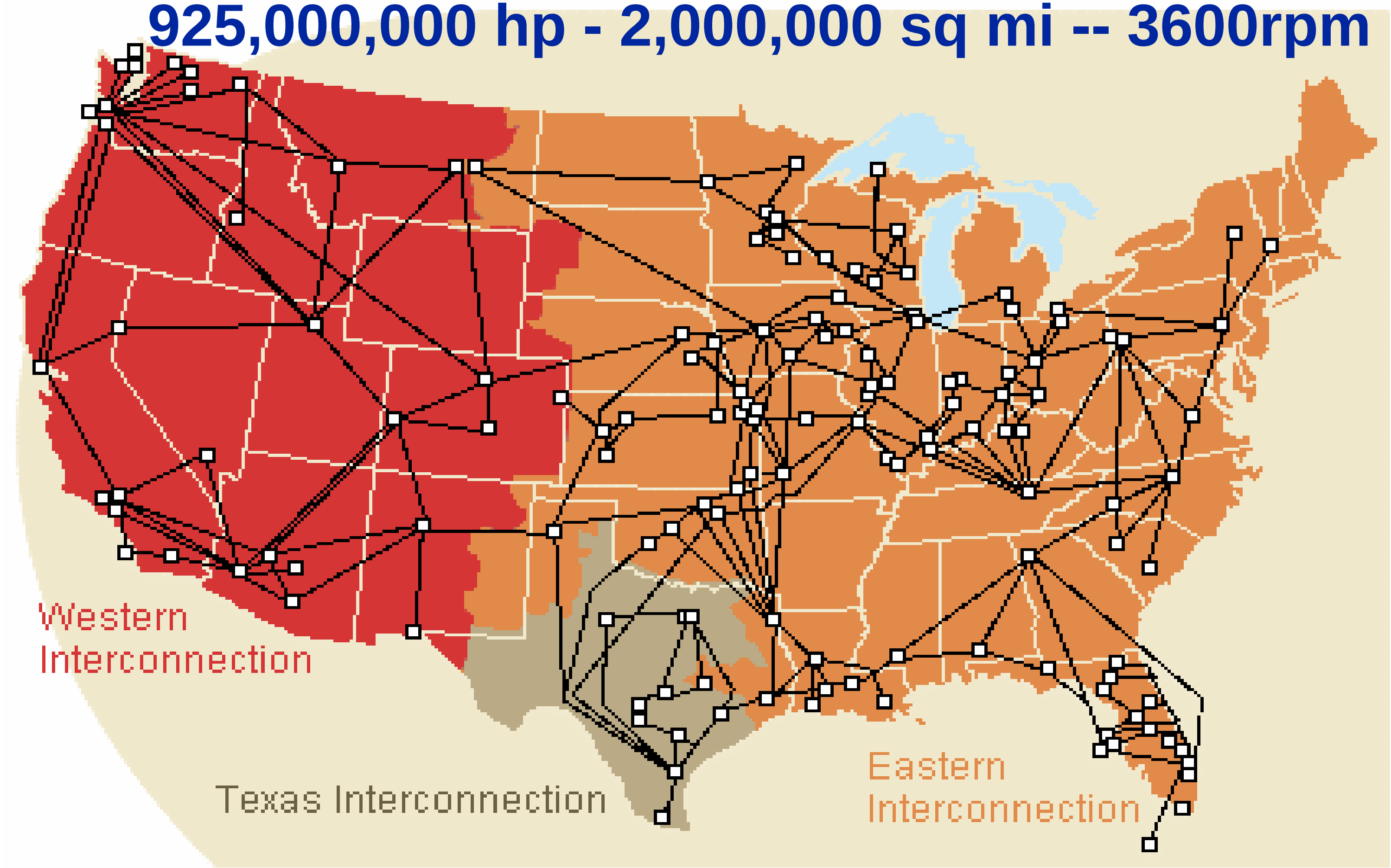
Keep in Mind – Fundamentals of Electricity Transmission

Generation must balance load in any area

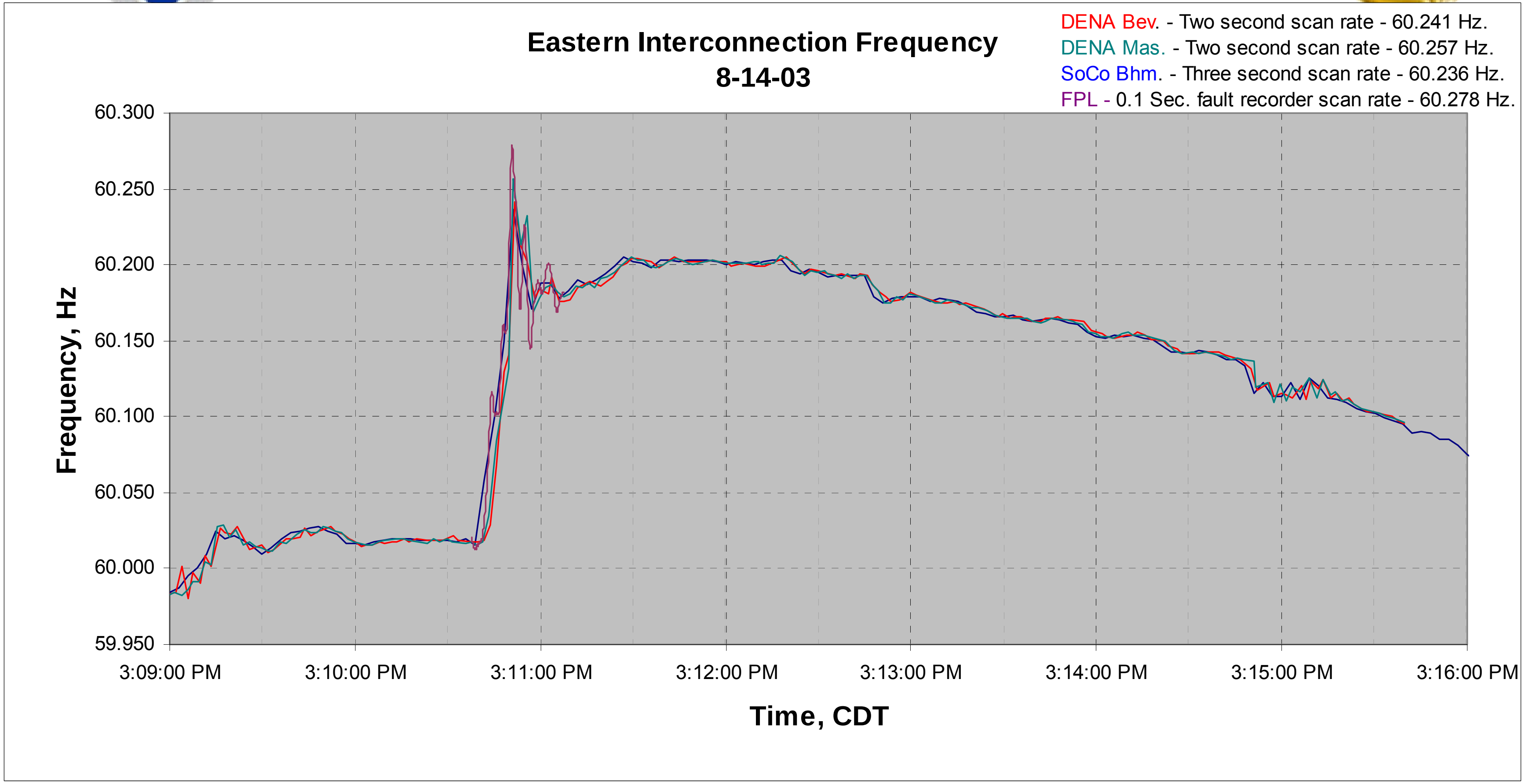


The US Grid

Eastern Interconnect-- “the World’s Biggest Machine”
925,000,000 hp - 2,000,000 sq mi -- 3600rpm



Frequency Excursions



By The Book

- The Book : Applied Protective Relaying by Westinghouse Electric Corporation, Coral Springs, Florida, 1982
- **The Basics :**
  - Normally Σ Generation = Σ Loads + Σ Losses
  - If Σ Generation ≠ Σ Loads + Σ Losses then $R = (pL(f_1 – f_0)/H(1-(f_1^2/f_0^2))$ where :
    - R = average rate of change of frequency (Hz/sec)
    - p = power factor rating of generators on system (assumed to be 0.85)
    - L = average per unit overload = (Load – Generation)/Generation
    - H = Inertia constant for system, MW-s/MVA (assumed to be $\cong$ 4)
    - f_0 = initial frequency
    - f_1 = final frequency

Note: Several of the following slides were “lifted” (by permission) from a presentation by Raymond Vice and Bob Jones of Southern Co Svcs

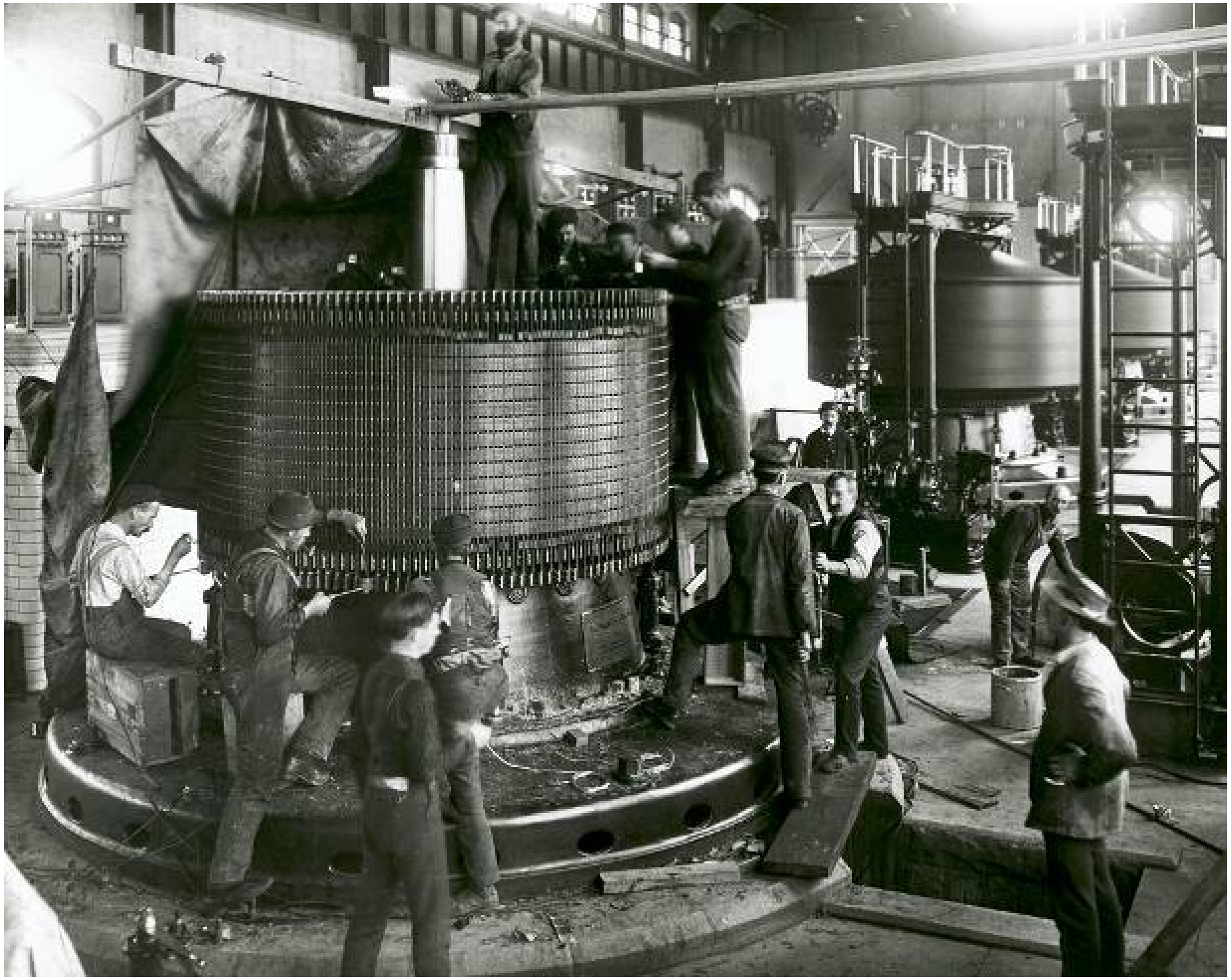
Implications

- Rate of frequency change, R, depends:
  - The Load/Generation mismatch
  - The inertia of the system
- Inertia of the system, H, is a factor of the inertia of the individual generators on the system :

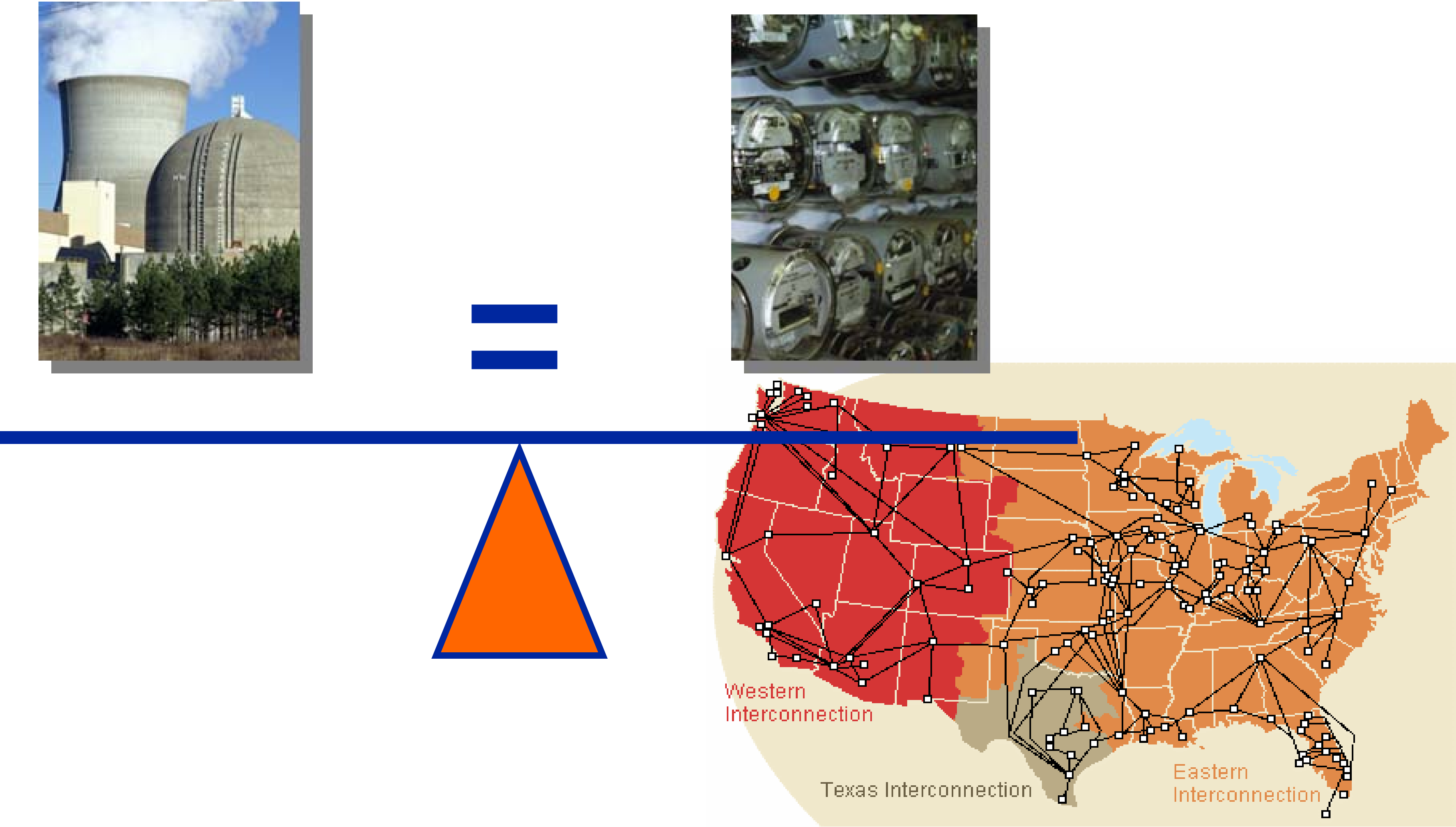
$$\mathbf{H_{System} = (H_1{*}MVA_1 + H_2{*}MVA_2 + H_N{*}MVA_N)/(MVA_1 + MVA_2 + \ldots + MVA_N)}$$

- Mass & RPM determine machine H
  - Hydro generators tend to have a high inertia (≈ 10)
  - Nuclear unit steam driven gen (4 pole)- relatively high inertia (≈ 5)
  - Older steam turbine driven gen- relatively high inertia (≈ 4)
  - Newer steam turbine driven gen- relatively low inertia (≈ 3)
  - Combustion turbine gen--relatively high inertia (≈ 4 or 5)

BIG H



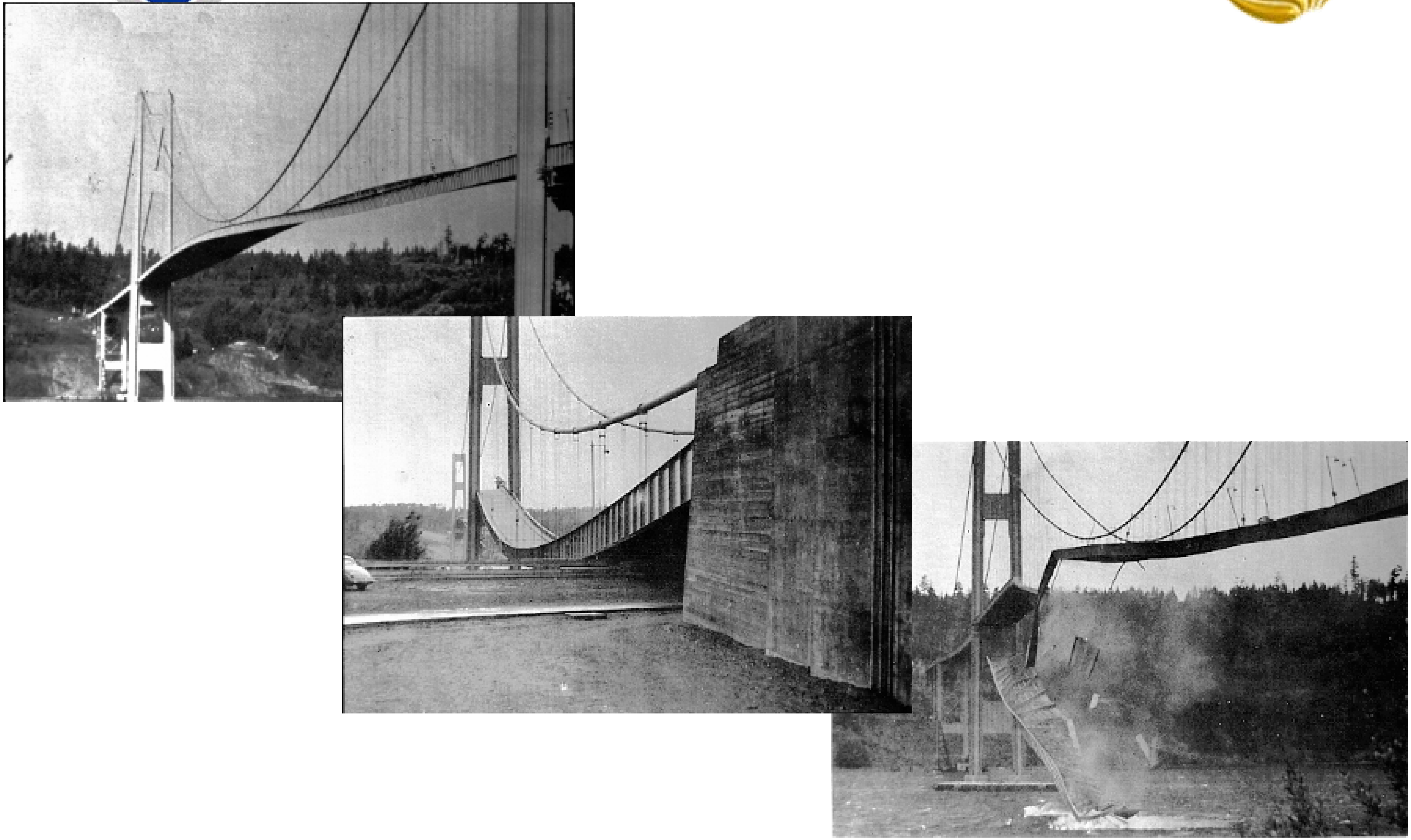
System Stability



Frequency Excursions

DISASTER!
The Greatest
Camera Scoop
of all time!

Frequency Excursions



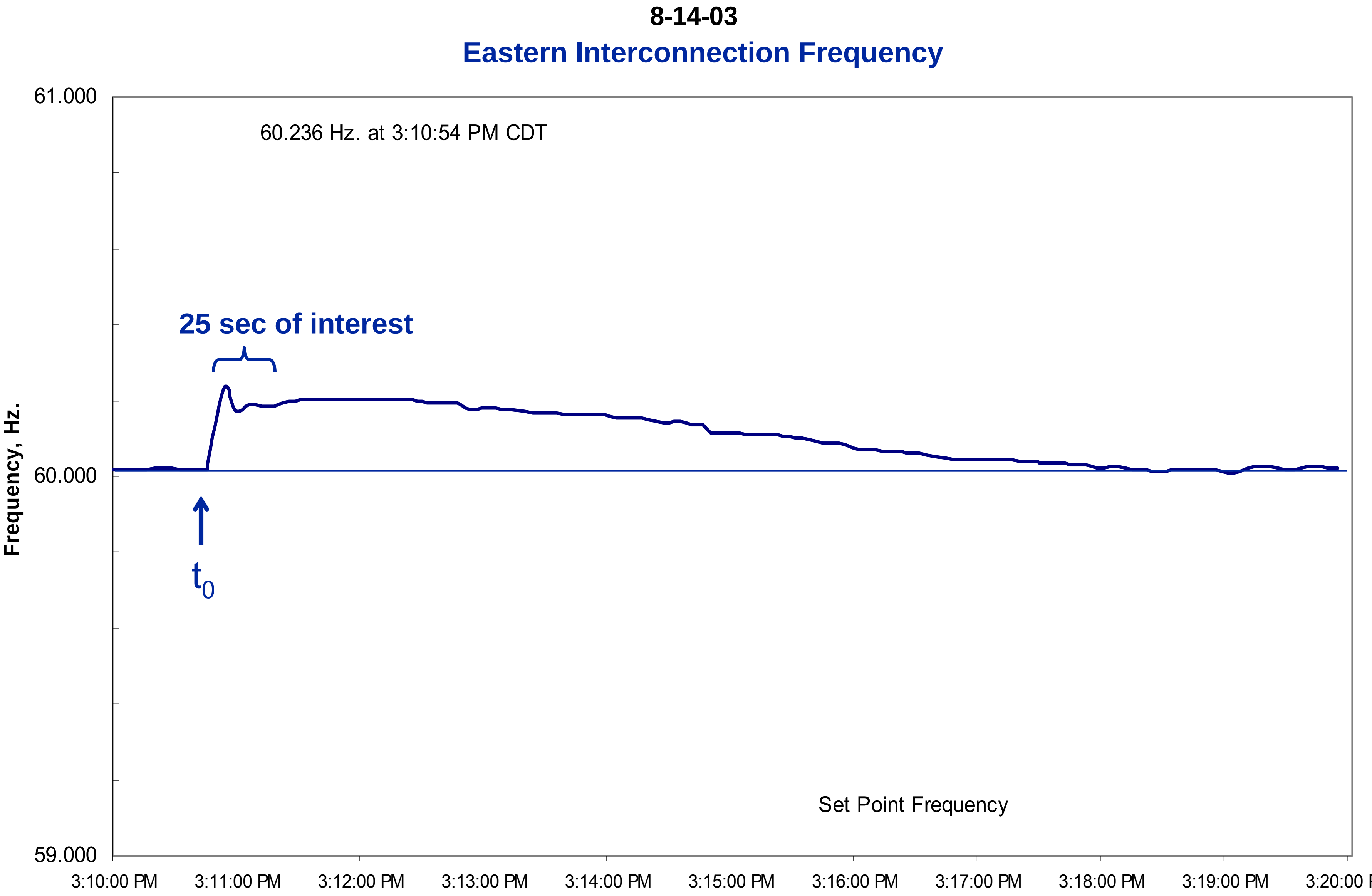
More Frequency Excursions

Near DISASTER !!

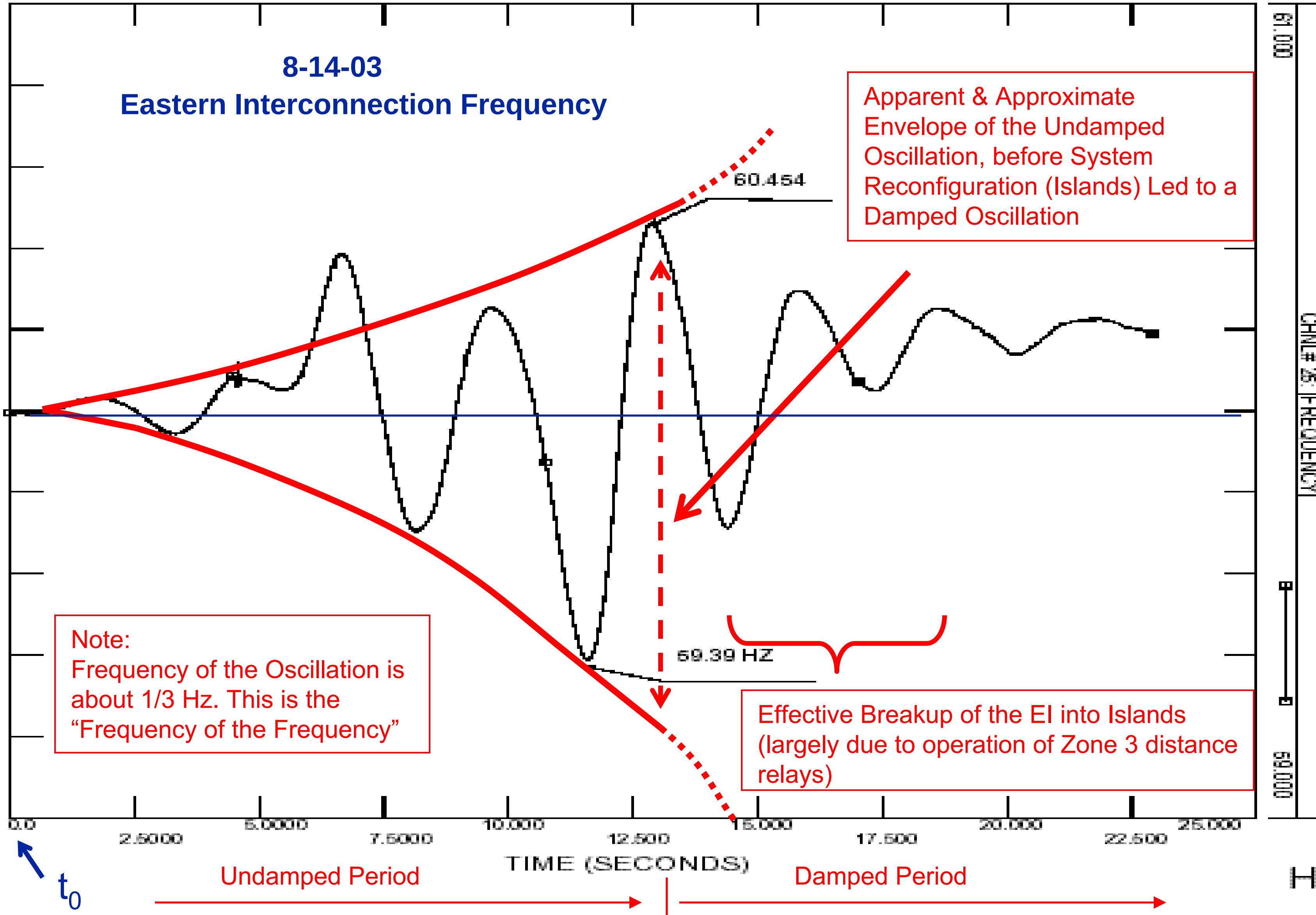
The Greatest Oscillograph Scoop of all time !

CRAZY FILMS

Frequency Excursions



Something Really Scary !



8-14-03

Eastern Interconnection Frequency

Apparent & Approximate Envelope of the Undamped Oscillation, before System Reconfiguration (Islands) Led to a Damped Oscillation

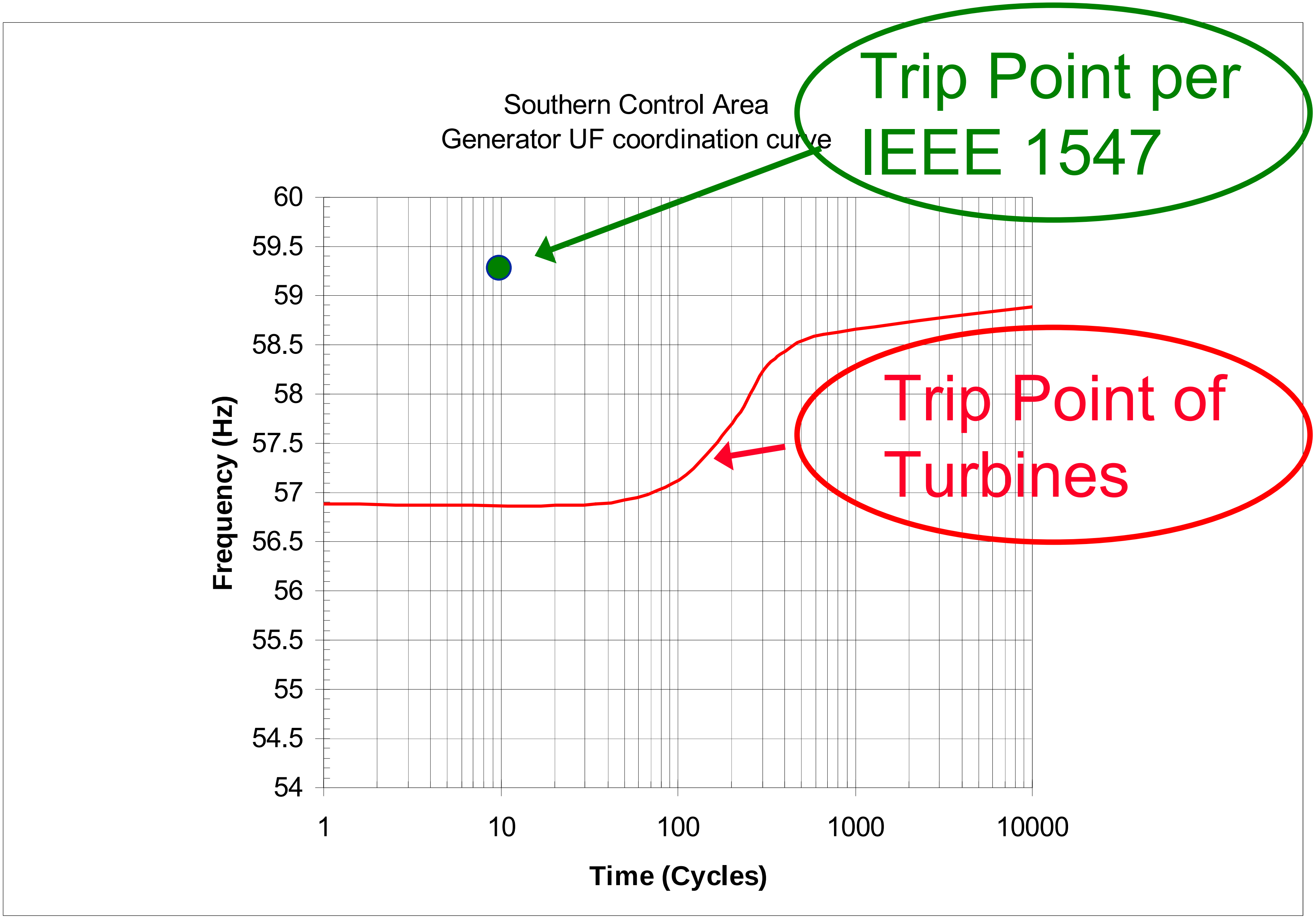
Note:
Frequency of the Oscillation is about 1/3 Hz. This is the "Frequency of the Frequency"

Effective Breakup of the EI into Islands (largely due to operation of Zone 3 distance relays)

Observation: <u>Must change</u>
Conclusion: <u>No UF trip</u>

- UF Load Shed only works if Gen<Load
- UF LS does not prevent initial transmission overloads
- UF LS only kicks in after Transmission islanding
- <u>Therefore</u>, Desirable that Gen <u>not</u> trip for UF
- This is in conflict with IEEE1547, etc. for non-islanding protection.
- If above solved, DC/Storage DG has a VERY HIGH EQUIVALENT “H Constant”, and can be very effective in Blackout Prevention
  - Note: Capacitors more effective than Batteries in the transient time frame, so a battery combined with ultracapacitor is the best combination

Storage is Good…..



Trip Point per IEEE 1547

Trip Point of Turbines

Result:

Upset:

Public

Politicians

Utilities

No Surprise:

- Utilities/Suppliers/Politicians:
  - seized on wrong solutions

Bogus Answers

- BO of 03 led to calls for:
  - More Central Station Generation
  - More Bulk Transmission
  - Loose 3rd zone relay settings – guarantees cascade

Real answers

- High penetration of DG – renewable only economic option
- Managed Island schemes
- Reconfigure grid- control areas separated by BtB DC links (convert AC lines)
- High impedance links w/ “frangible” relay settings
- Better Maintenance (TT, etc)

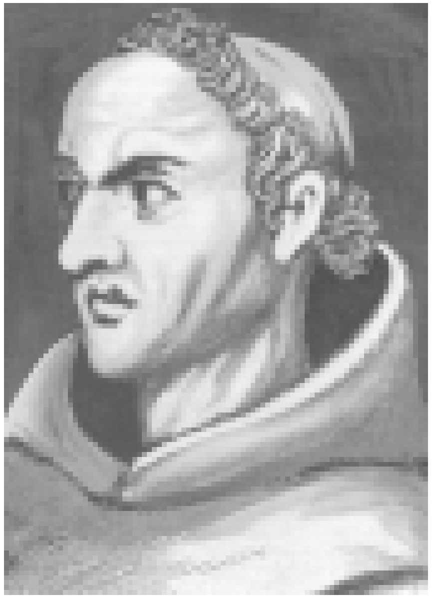
3 Phase Power

Actually, a “Blinding Flash of The Obvious”…

Idea: DC at “The Links”

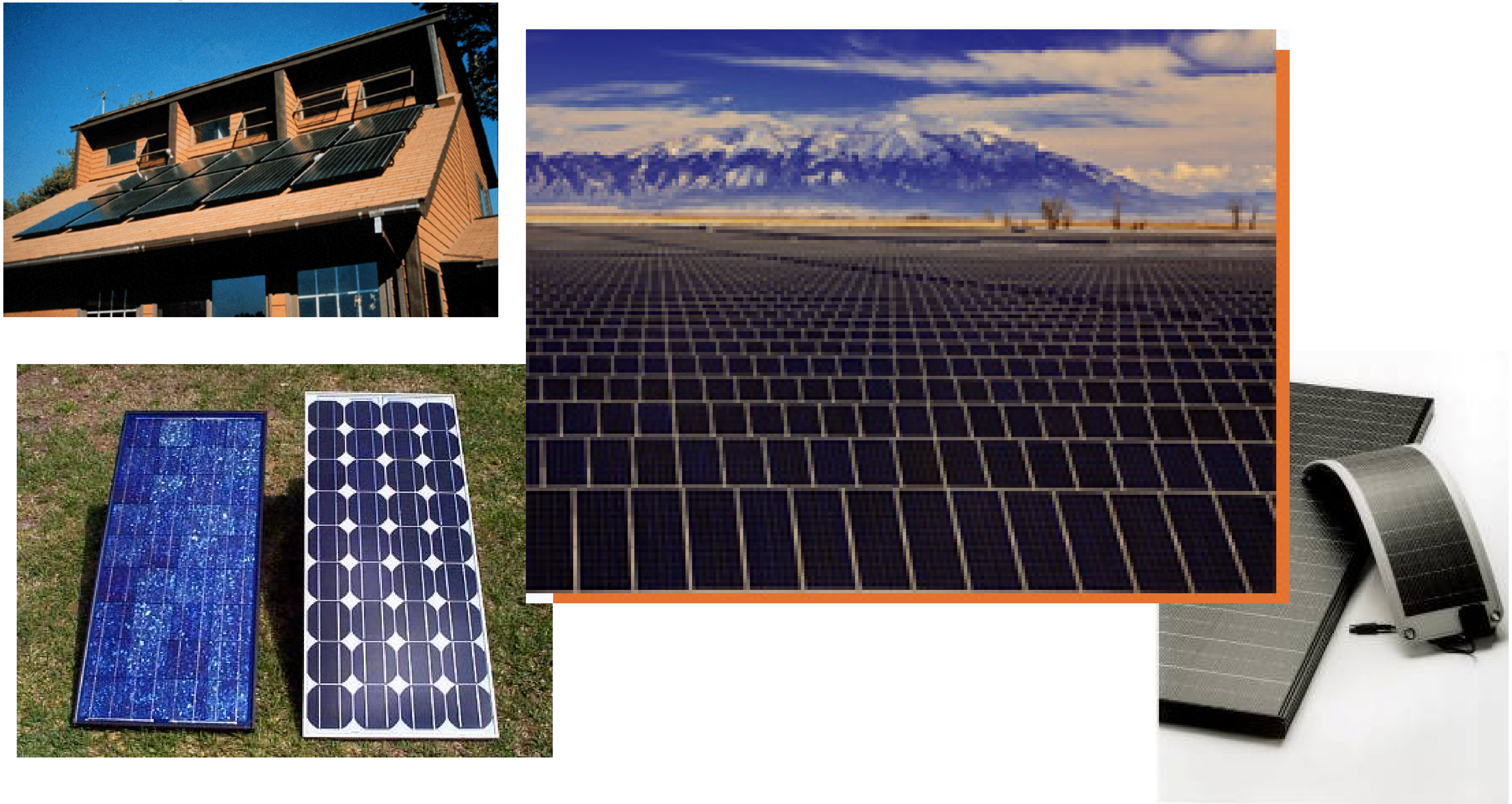
- **Generation at BtB Links:**
  - Natural DC Sources
  - “Un-Natural” DC Sources
- **Storage Injection at BtB Links**
- **Control Areas Finally take Control:**
  - Reactive Power Control (VAR)
  - Real Power Control
  - Phase Balance (reduce Negative Sequence)

Another Idea:

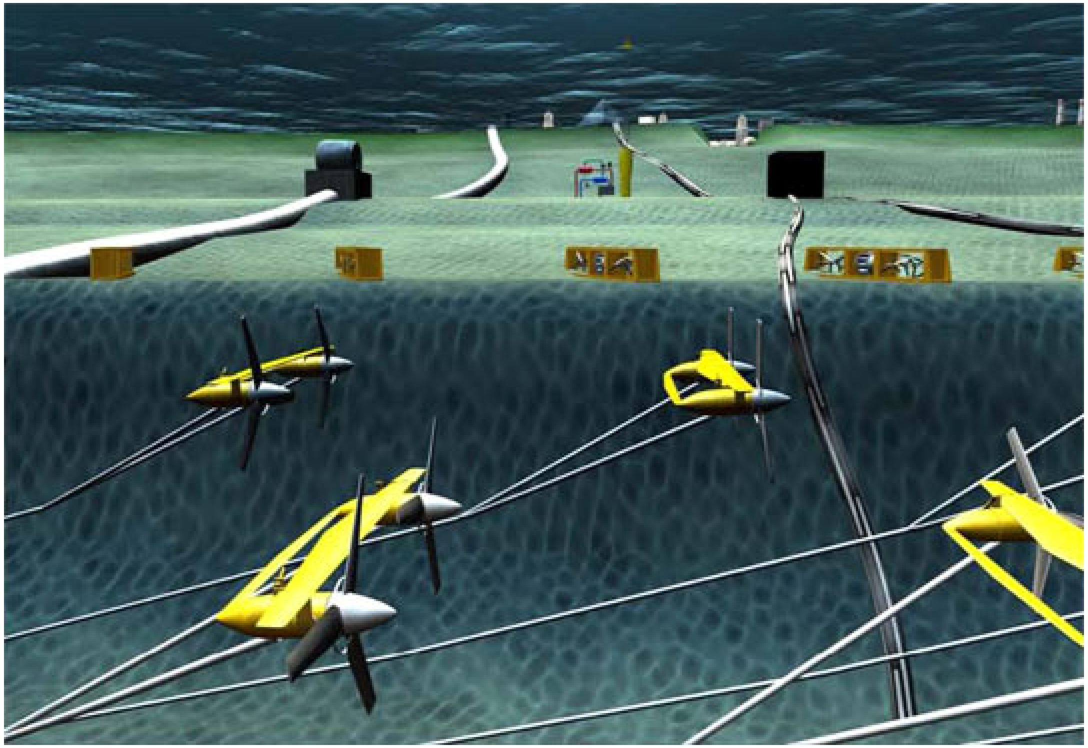


- Control Areas Use Permissive PLCC to Maintain Generation During Disturbances
  - No Freq Push issues with high penetration
  - Certainty with down lines
  - Provides CA Shutdown Capability during Over Gen

Natural HMW DC Sources – PV Arrays

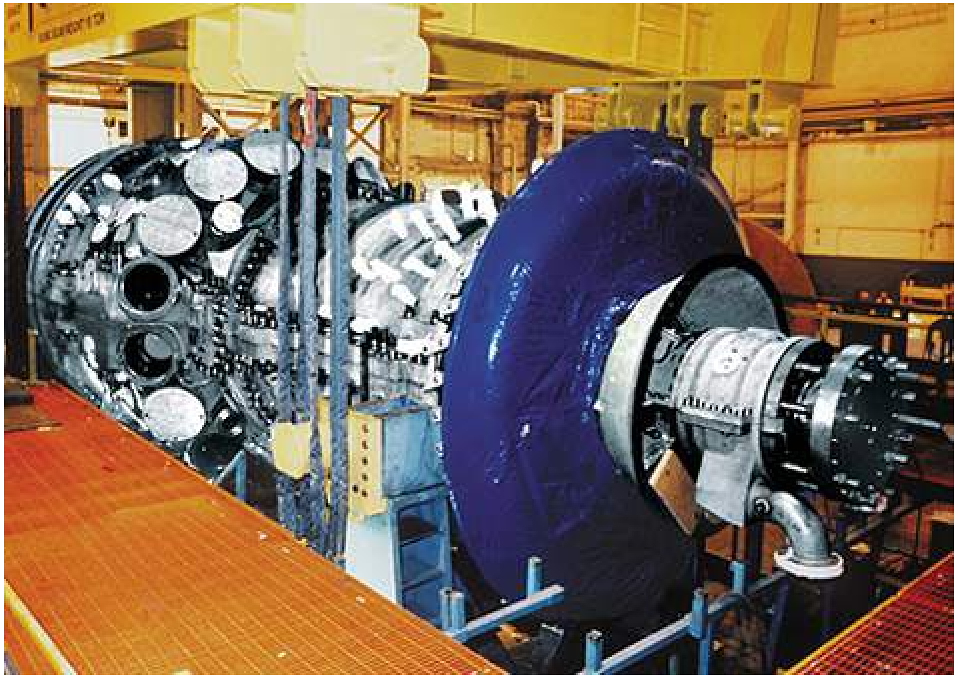


Natural HMW DC Sources – Wind & Ocean



Un-natural MW DC sources: GTs

- DC output relieves many constraints, with high RPM, smaller mass



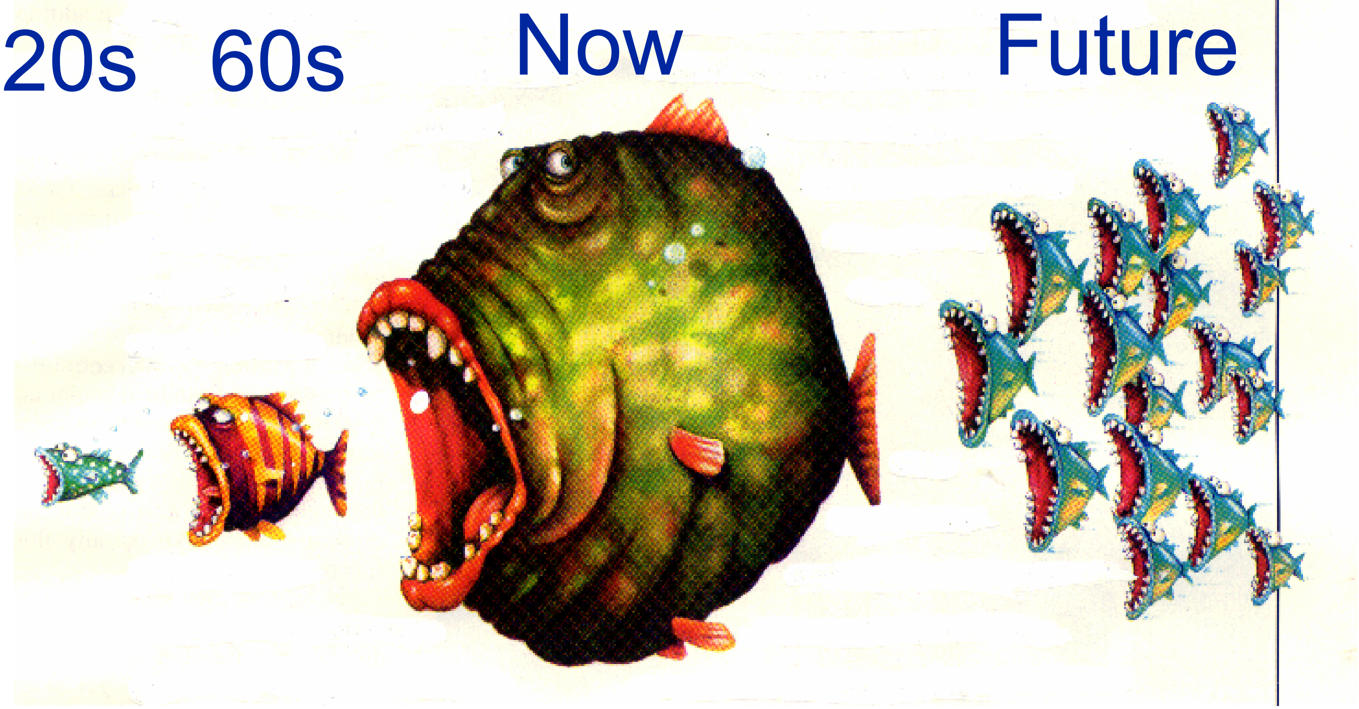
Utility Needs: HMW Converters

- Stay online until at least 58 Hz
  - ➔ PLCC Permissive for DG
- Ability to call for VAR support (w/compensation)
- Ability to call forth storage (w/ comp)
- Ability to shutdown DG by area
- Need transient power boost (equiv H)- spinning Resv
- Need 10 min reserve (mimic quick start peakers) from storage
- Need long term reserve from storage

Old View – Island BAD

New View – Island GOOD

System Evolution



Florida Solar Energy Center

Creating Energy Independence Since 1975

A Research Institute of the University of Central Florida

GE
Energy

Wind Energy Technologies

Sumit Bose
GE Energy
April 8, 2008

Bose@ge.com
518-385-5785

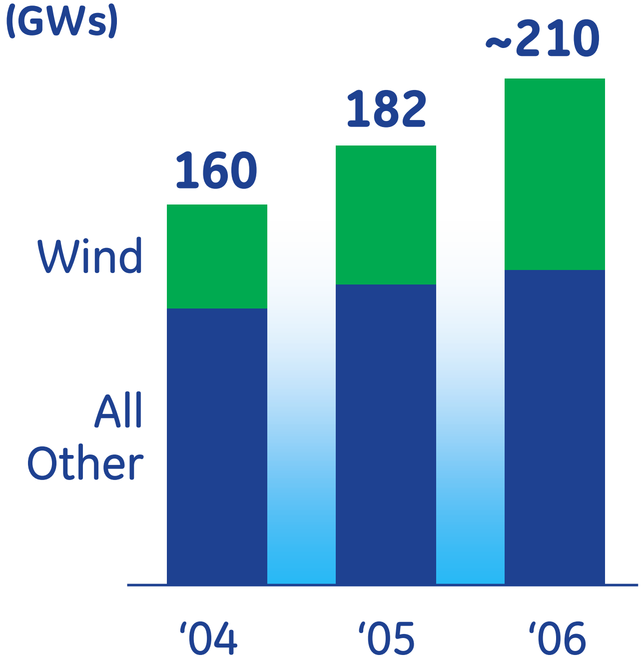
imagination at work

The need for change … and choice

- Global Population Growth
- Energy Consumption
  +50% by 2020
- Fossil Reserves ?
- Environmental Impact?
- Alternatives ?

Growing renewables demand …

Global renewable installed capacity



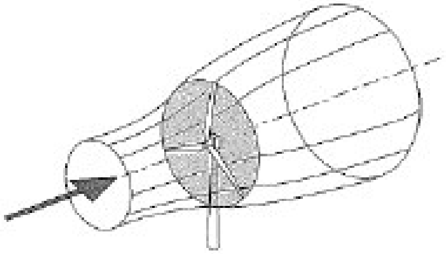
Source: REN21 2006 update + GE est (9/07)

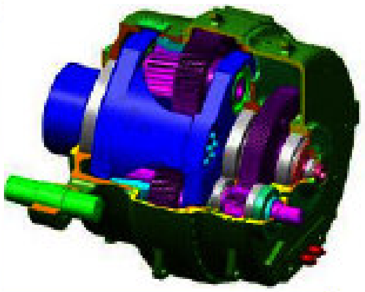
- Significant growth … 25% CAGR ('01-'06)
- 40% power capital spending
- Wind >50% of growth
- Domestic, abundant, carbon-free
- Countries & US states establishing renewable energy targets

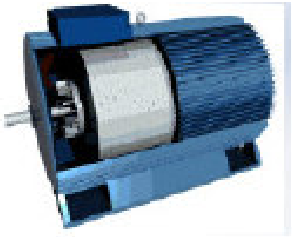
World requiring renewable energy solutions

Wind turbine principles

The basic idea is to convert one energy form into another







Kinetic Energy → Mechanical Energy → Electrical Energy

Rotor
45 - 52%

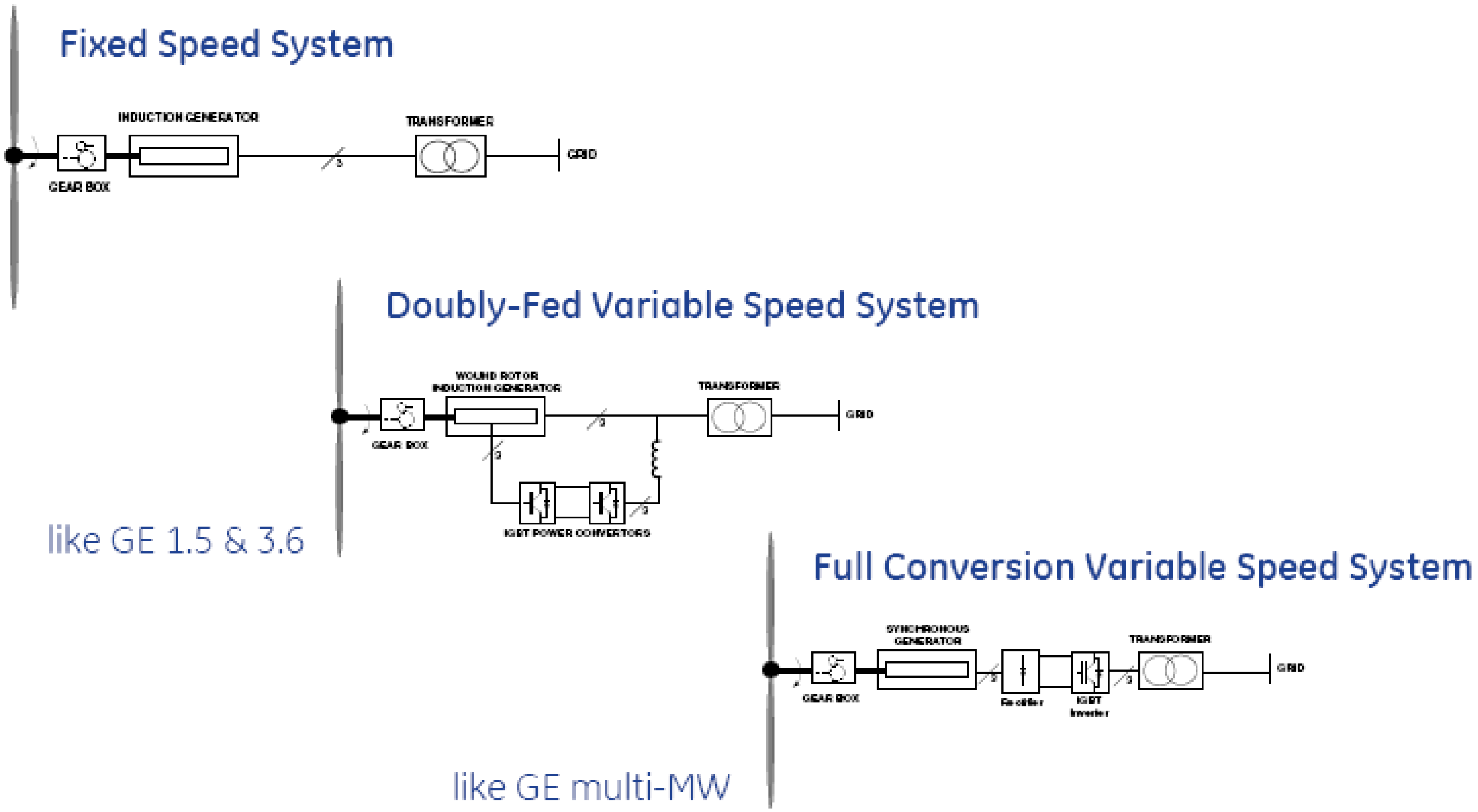
Gearbox
95 – 97%

Generator +
Power Converter
90 – 95%

42 – 50% Efficient Today… Theoretical Maximum is 59% (no losses)

Electrical power conversion

Fixed-speed to variable-speed



Fixed Speed System

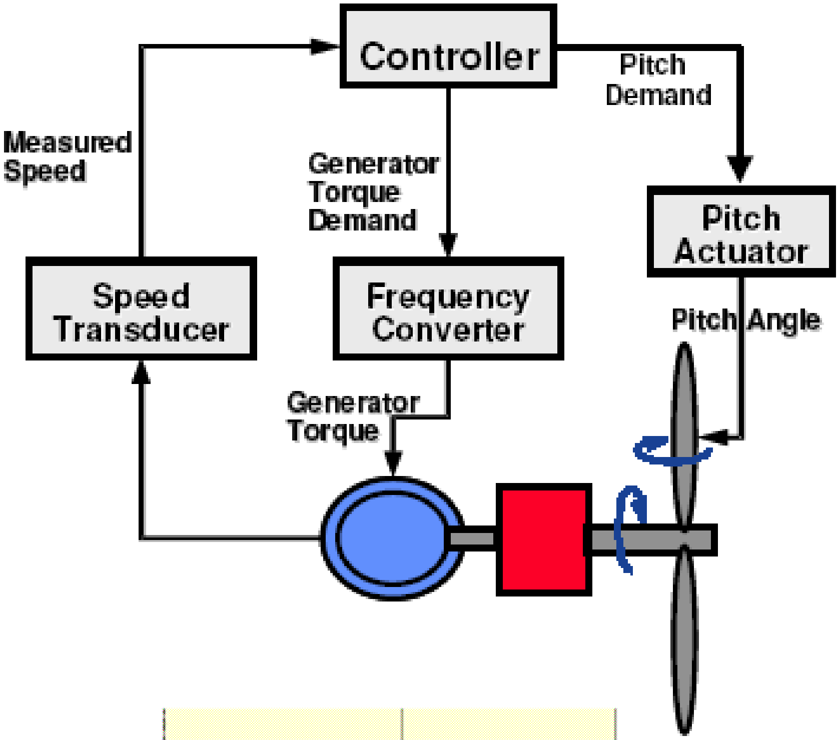
Doubly-Fed Variable Speed System

like GE 1.5 & 3.6

Full Conversion Variable Speed System

like GE multi-MW

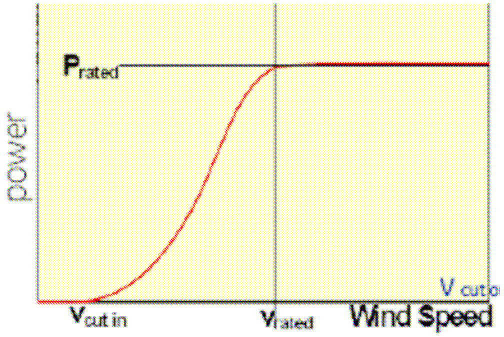
Variable speed + pitch regulated control



Closed loop control based on rotor speed and torque demand

Speed and Output controlled by blade pitching

Overspeed Protection also performed by blade pitching



Maintain tip speed ratio until rated wind speed

Maintain rated output after rated speed

GE 1.5 MW turbine family

1.5 Wind Turbines				
	1.5e	**1.5se**	**1.5s**	**1.5sle**
Frequency	60Hz	50/60Hz	50/60Hz	50/60Hz
Wind Regime	IEC TC Ia+	IEC TC Ib	IEC TC IIa	TC III/s
Rotor Diameter	65m	70.5m	70.5m	77m
Rated Power	1.5 MW	1.5 MW	1.5 MW	1.5 MW
Hub Heights	65m	52-65m	65-85m	61-85m
Speed Range	11-22 rpm	11-22 rpm	11-22 rpm	10-20 rpm

GE Developments

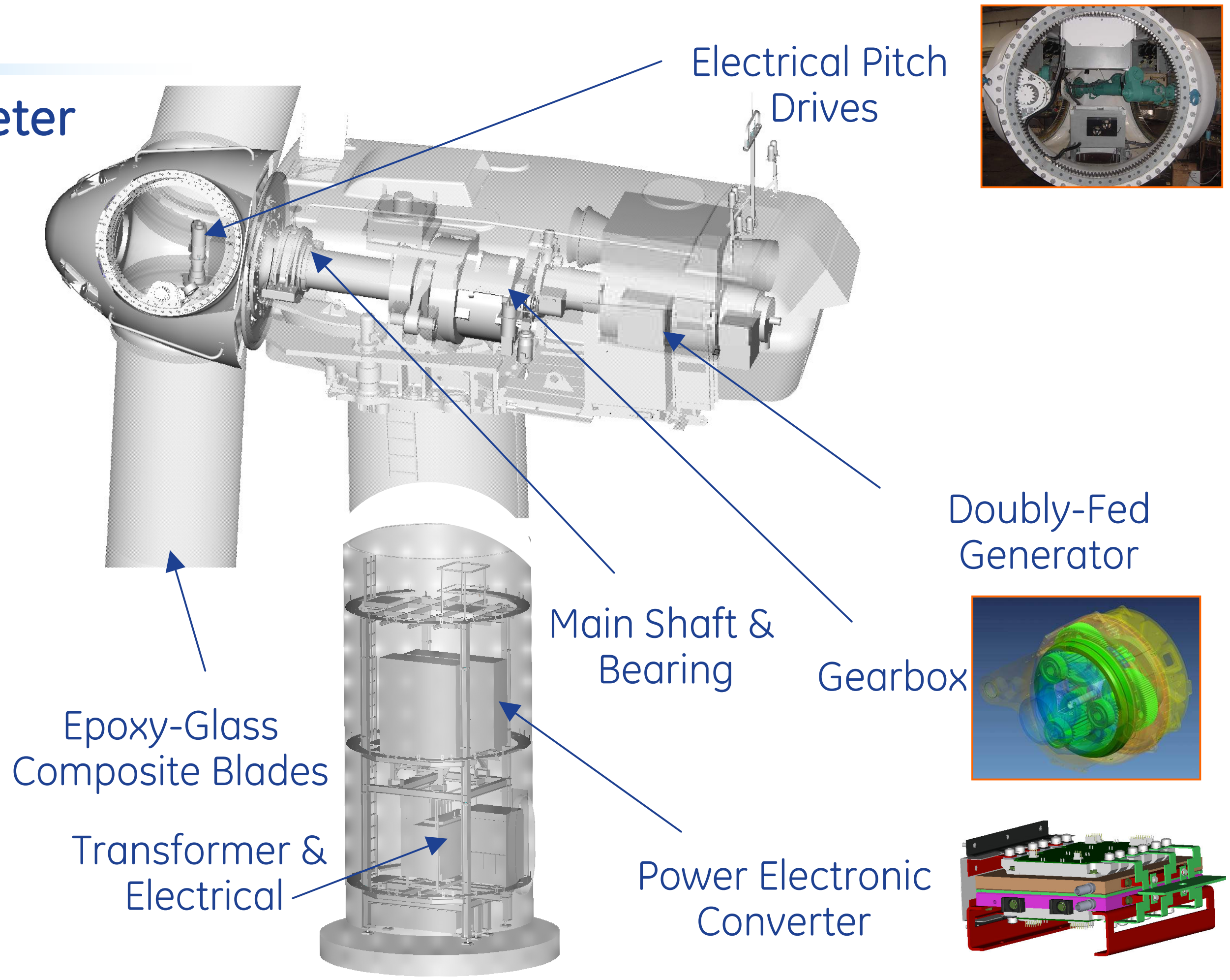
- Industry workhorse
- Reliability Growth
- COE Reduction, Global Sourcing
- Extended Operations – Temp, IEC TC I/II

imagination at work

Wind turbines

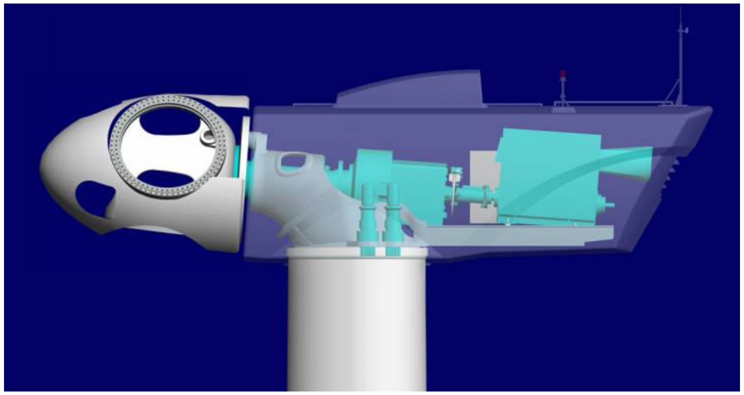
GE 1.5 MW

- 77 M Rotor Diameter
- 50-100 M Tower
- 98% Availability
- Speed 10-20 RPM
- Variable Pitch



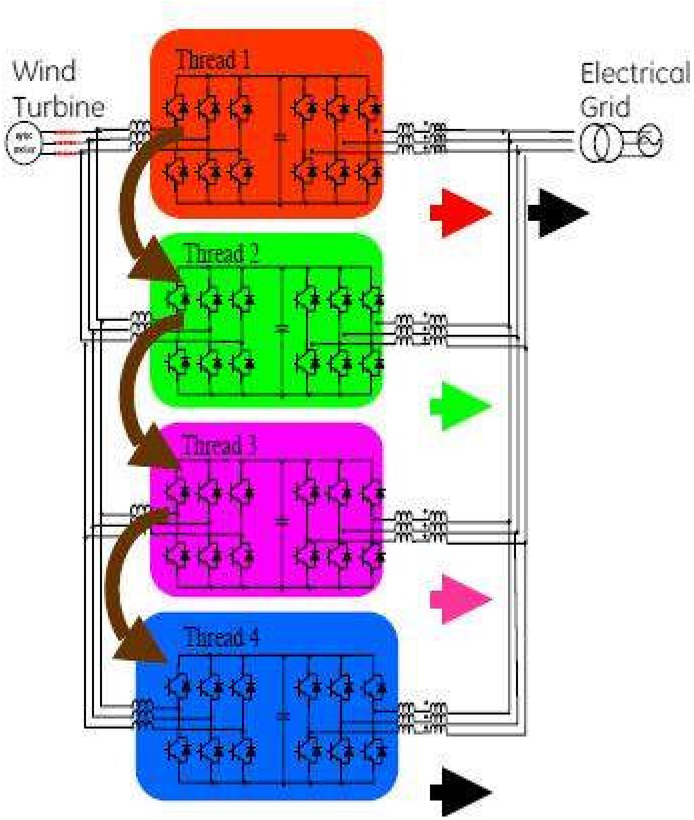
GE 2.x turbine family

2.x Wind Turbines		
	2.3	**2.5**
Wind Regime	IEC TC IIIa	IEC TC IIa
Rotor Diameter	94m	88m
Rated Power	2.3 MW	2.5 MW
Hub Heights	100,120m	85m
Avg Wind Speed	7.5 m/s	8.74 m/s



Features

- Common platform IEC classes
- Common 50/60 Hz design
- Full power conversion
- Double main bearings

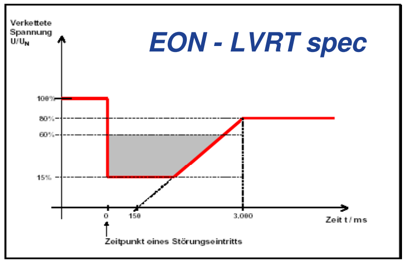


imagination at work

Utility scale wind generation …
5-10% penetration easily managed

150 MW Trent Mesa, TX

Utility Windfarms



100-500 MW Farms Being Developed

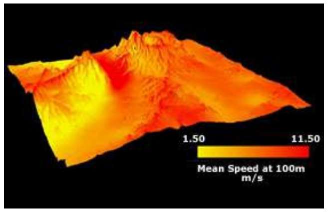
- Grid Codes Rapidly Evolving

Danish Transmission Grid w/
Interconnects & Offshore Sites

Jutland - Western Denmark

3000 MW Wind Capacity Out of 6800 MW Total

- 20% of Average Demand Supplied by Wind
- Max 1 Hr Penetration Is 80%, max 20% change per hour
- HVDC Link to Norway, Hydro As Virtual Storage



Wind Site Forecasting

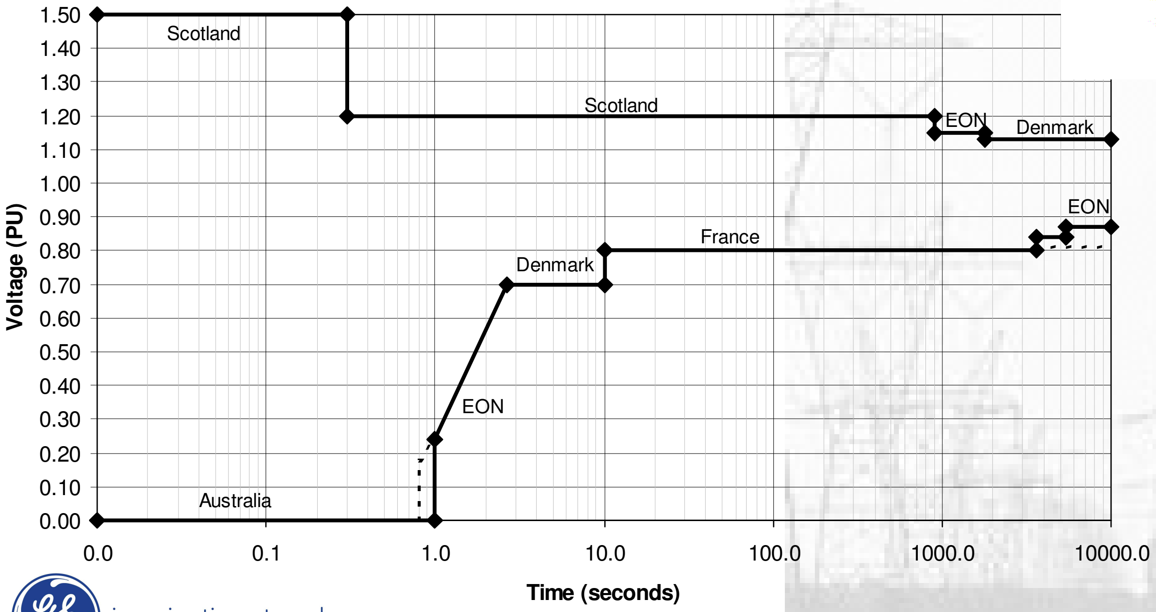
Managing a Variable Resource

- 1 to 48 Hour Wind Forecasting
- Coordinated Economic Dispatch of Hydro, GT, ….

Grid integration …critical for large scale wind

Rapidly Evolving Grid Codes

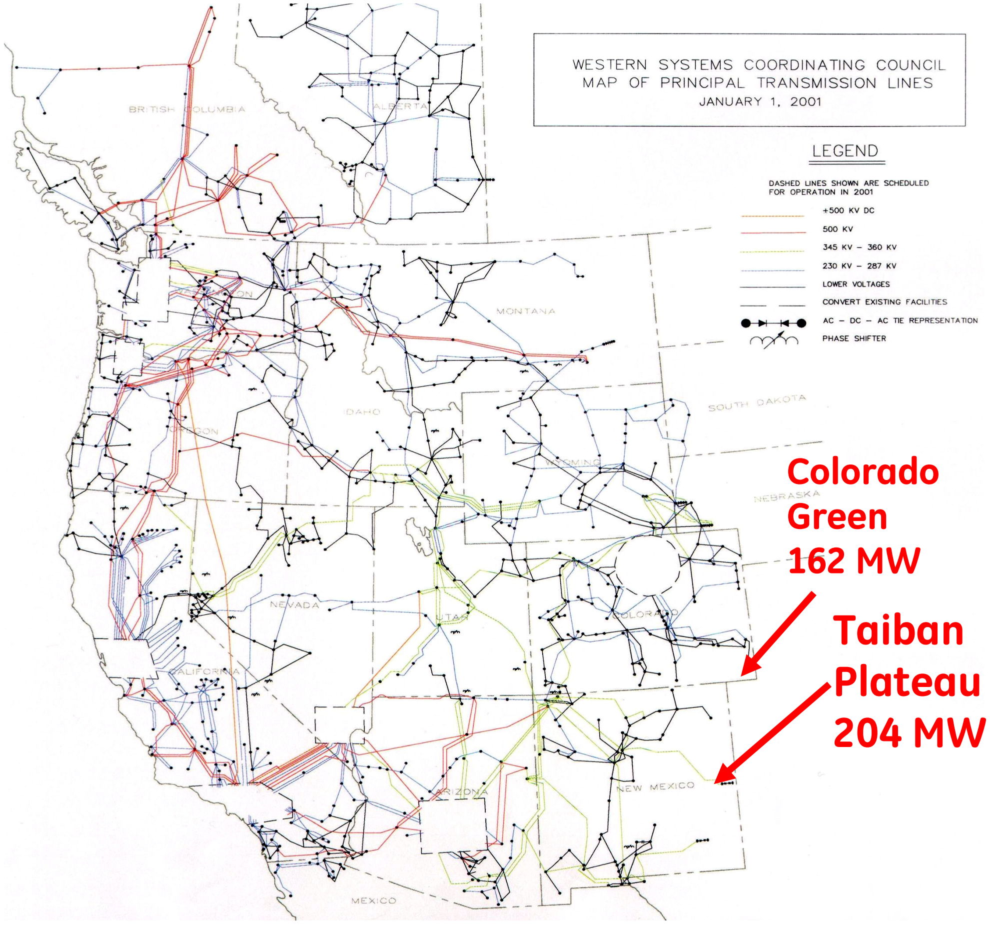
- Success of wind is driving sweeping changes
- New electrical control features evolving
- Ride-Thru, Real/Reactive Power control
- Wind needs to be as Grid-Friendly as Traditional Generation for 50 GW Global market



Global Transient Voltage Requirements

imagination at work

Windfarm electrics – real & reactive power control

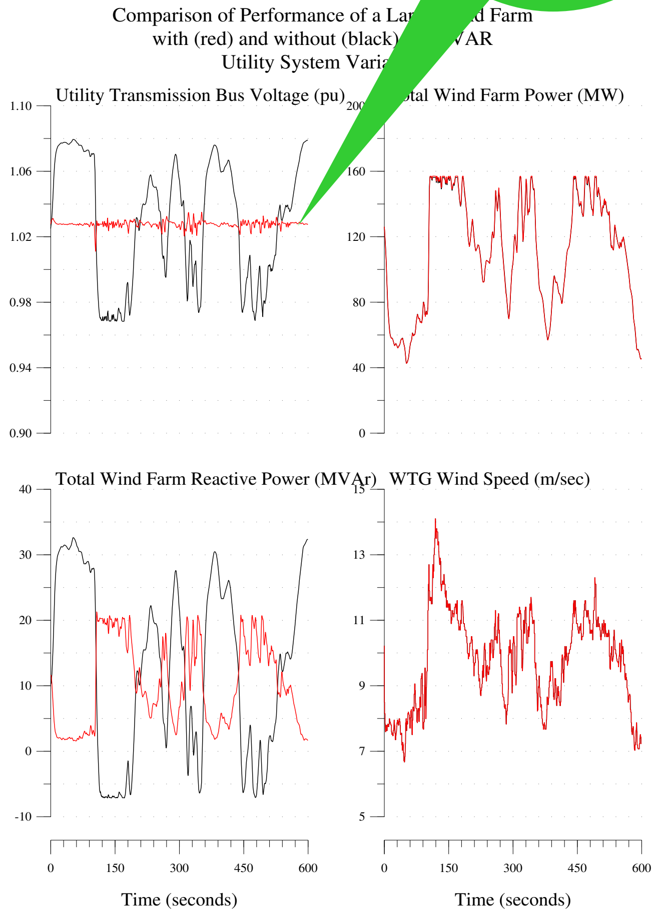


Colorado Green 162 MW

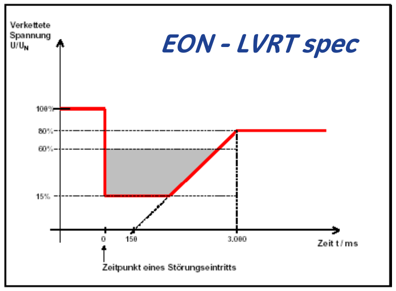
Taiban Plateau 204 MW

~ **1500 mi**

Clean volts on host utility grid



Grid requirements evolution


EON - LVRT spec

Performance Requirements

Advanced

Basic

Active Anti-islanding, Torsional, others	Zero Power Voltage Control	LVRT with controlled current injection	Reserve Functions
Anti-islanding	Fancy Voltage Control (WindVAR)	Zero VRT – no trip	Frequency Response
	Voltage control	LVRT – no trip	Curtailment
O/U Voltage Overcurrent O/U Frequency	PF control	None	None
Protection	**Volt/VAR Control**	**LVRT**	**Active Power Control**

Application Characteristics

Single WTGs　Large Farms　Multiple Farms

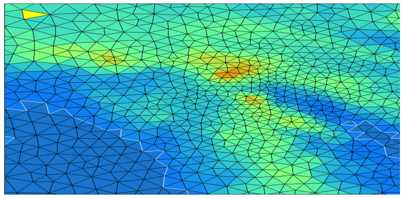
Low Penetration　High Penetration

imagination at work

Power generation firming & smoothing

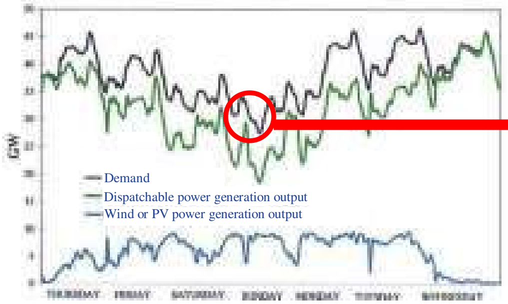
Slow - Generation Firming

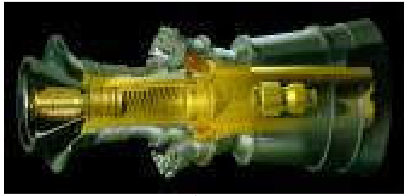
Wind



Advanced Forecasting

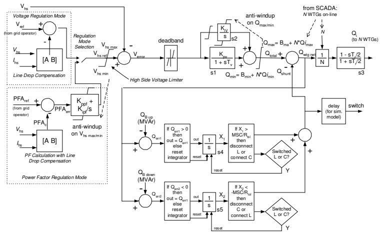
Storage





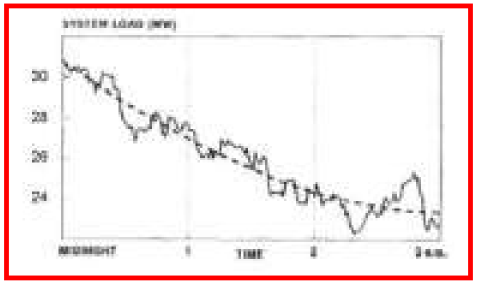
Advanced Generation

Fast - Generation Smoothing



Advanced Power Controls

Active Demand Participation



A full suite of technologies will enable high renewables penetration:

Forecasting + Controls + Storage + Advanced GT + Active Load Control

Wind Energy Technologies

Sumit Bose
GE Energy
April 8, 2008

Bose@ge.com
518-385-5785

GE imagination at work

DOE High-Megawatt Power Converter Technology R&D Roadmap Workshop

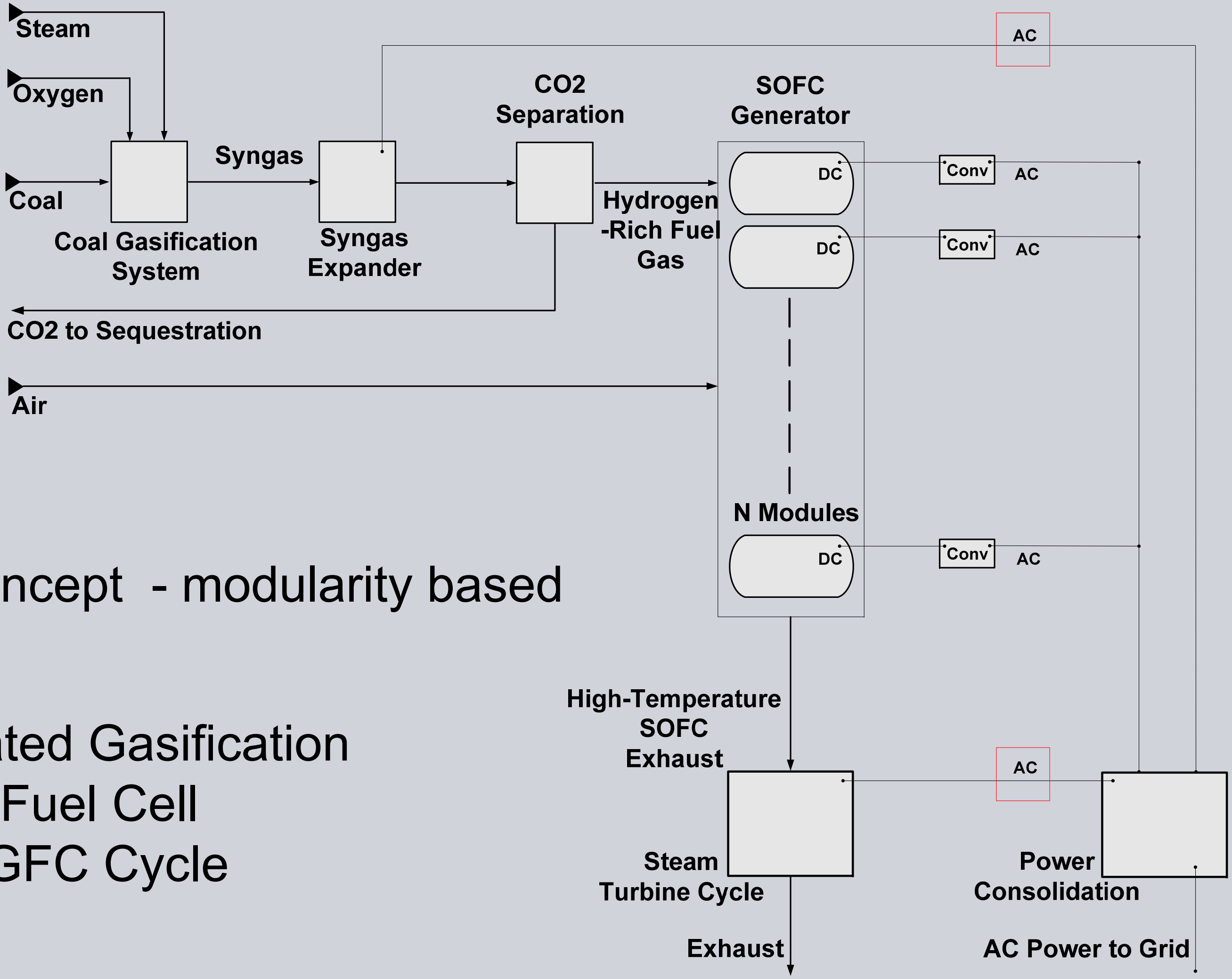
Tom Gordon April 8, 2008 NIST Gaithersburg, MD

DOE Integrated Coal Gasification Fuel Cell System with CO_2 Isolation

A Multi-Year, Multi-Phase Cost Shared Program

- **Coal Syngas fueled, 100 MWe class fuel cell central station**
- **Efficiency > 50%, (based on HHV but excluding CO_2 Sequestration)**
- **90% CO_2 Sequestration Potential**
- **$400/kWe (power island)**
- **Integrated Gasification Fuel Cell Cycle …IGFC Cycle**

DOE Integrated Coal Gasification Fuel Cell System with CO_2 Isolation



Evolving concept - modularity based

Integrated Gasification
Fuel Cell
IGFC Cycle

Direction –How To Realize High Power System

- High power ratings will be accomplished with Multiple Modules of Fuel Cell Power Blocks.   Limitations include:

- Specific power (kWe/m^3) ratings –transportation issues
- Avoidance of flow and thermal asymmetries
- Maximize current loading of the actual fuel cells –multiple modules foster this goal
- Fuel cell stack dielectric system limitations

Direction –Characteristics of Basic Fuel Cell Module

SIEMENS

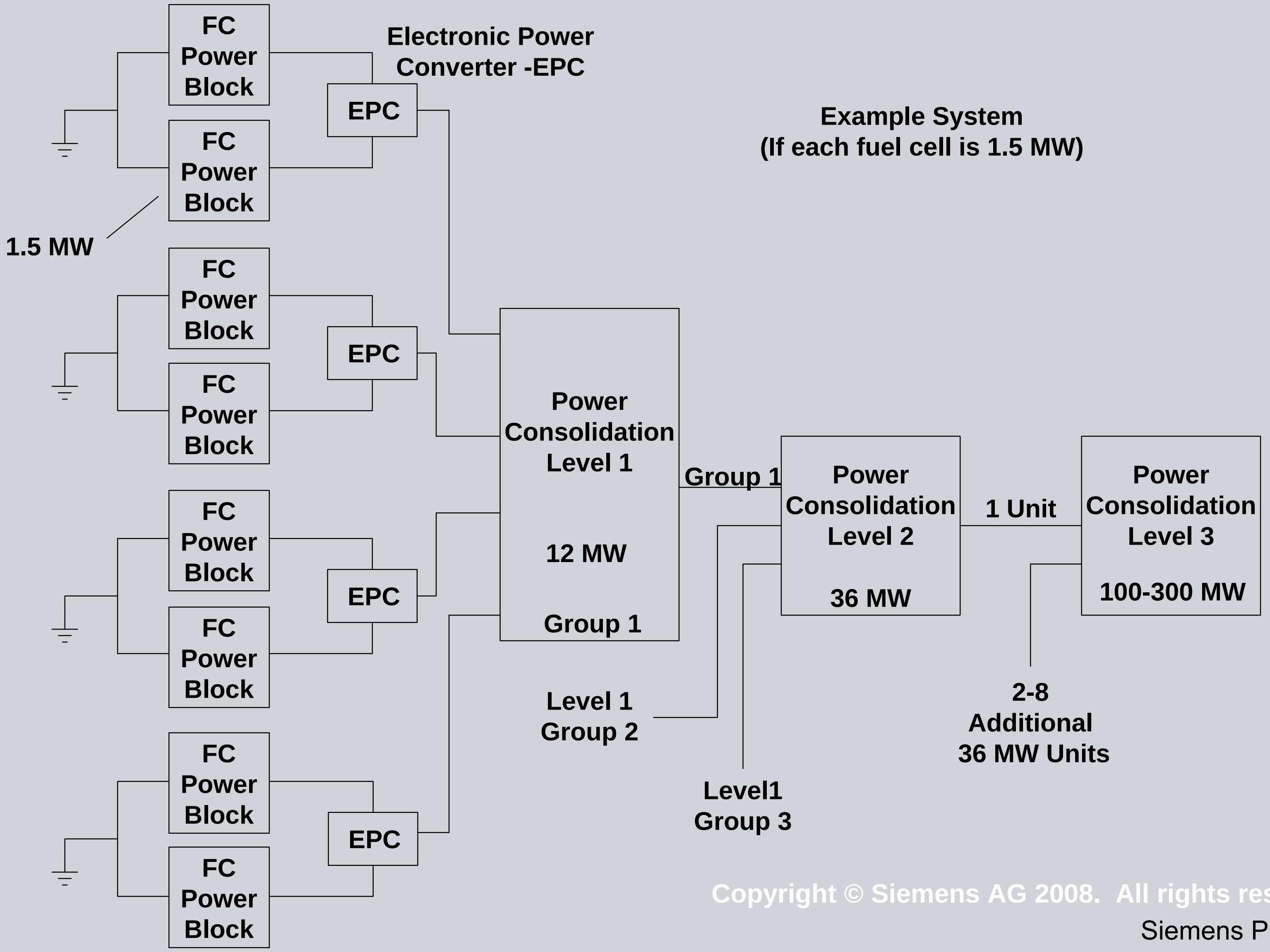
- **Fuel cells are a soft voltage source –poor terminal voltage regulation under load**
- **Present SOFC's terminal voltage drop under fully loaded conditions may approach a ratio of nearly 2:1 vs. the maximum Vdc open circuit for the fuel cell**
- **SOFC modules for the IGFC system are expected to be in the range of 1000 Vdc open circuit and the 1000 ampere class**
- **Terminal voltage regulation improvements are anticipated but nevertheless this issue still must be accounted for … along with transient excursions too**

Direction –Requirements for PCS Topology

- PCS topology must aggregate power from many fuel cell modules
- Topology must support individual current loading of the fuel cell modules … (or minimum groups)
- Topology should permit individual modules and electronics to be taken off line while the system continues to run … (or minimum groups)
- The fuel cell modules would not be at tightly uniform DC voltages
- The PCS also must integrate AC power from generators used to recover exhaust heat energy
- An example system is presented in the next slide

System to Consolidate Fuel Cell Power

SIEMENS



Example System
(If each fuel cell is 1.5 MW)

Elements Needed / Power Consolidation Essential

- High power/ modular/ cost efficient/ loading control circuit building block (EPC-electronic power converter)
- Modular EPC for 0.7 to 2 MW fuel cell module
- Performance optimized and cost efficient power consolidation methods
- Power consolidation can be either DC based (capacitors) or AC based (transformers)
- Optimal inverter aggregation methods
- Practical and efficient transformer combinatory techniques

Elements Needed / Power Consolidation Essential

Perspective of what is needed for larger converter systems

Efficient consolidation methods are needed to aggregate the power from many small approximately 1 MW fuel cell units

Viewpoint: It is important that methods to aggregate and combine the power must be identified, compared and evaluated. The inverter per se is not the challenge.

A viable IGFC system at the 100-300 MW level will require virtually hundreds of small converter power groups to be efficiently strung together and consolidated to create one large plant

Power & Voltage Level Check

- from an EPRI study:

15 kV $_{L\text{-}L}$ class circuit _peak load 4-6 MVA

25 kV $_{L\text{-}L}$ class circuit _peak load 7-10 MVA

35 kV $_{L\text{-}L}$ class circuit _peak load 10-16 MVA

- Check Power Capability:

115 kV L-L @500A = 100 MVA

Power & Voltage Level Check

- Previous slide demonstrates high voltage systems are needed to deliver the power level of interest
- The same logic would apply to the converter system if enough power can be consolidated to supply higher level types of power converters
- Conclusion: Examination of PWM inverter systems is very appropriate. But possible use of higher power multi-pulse stepped square wave inverters also should be considered.
- Stepped square wave inverters are GTO based line frequency switching utility grade inverters …100-500+ MVA class. Applications SVC, FACTS, HVDC

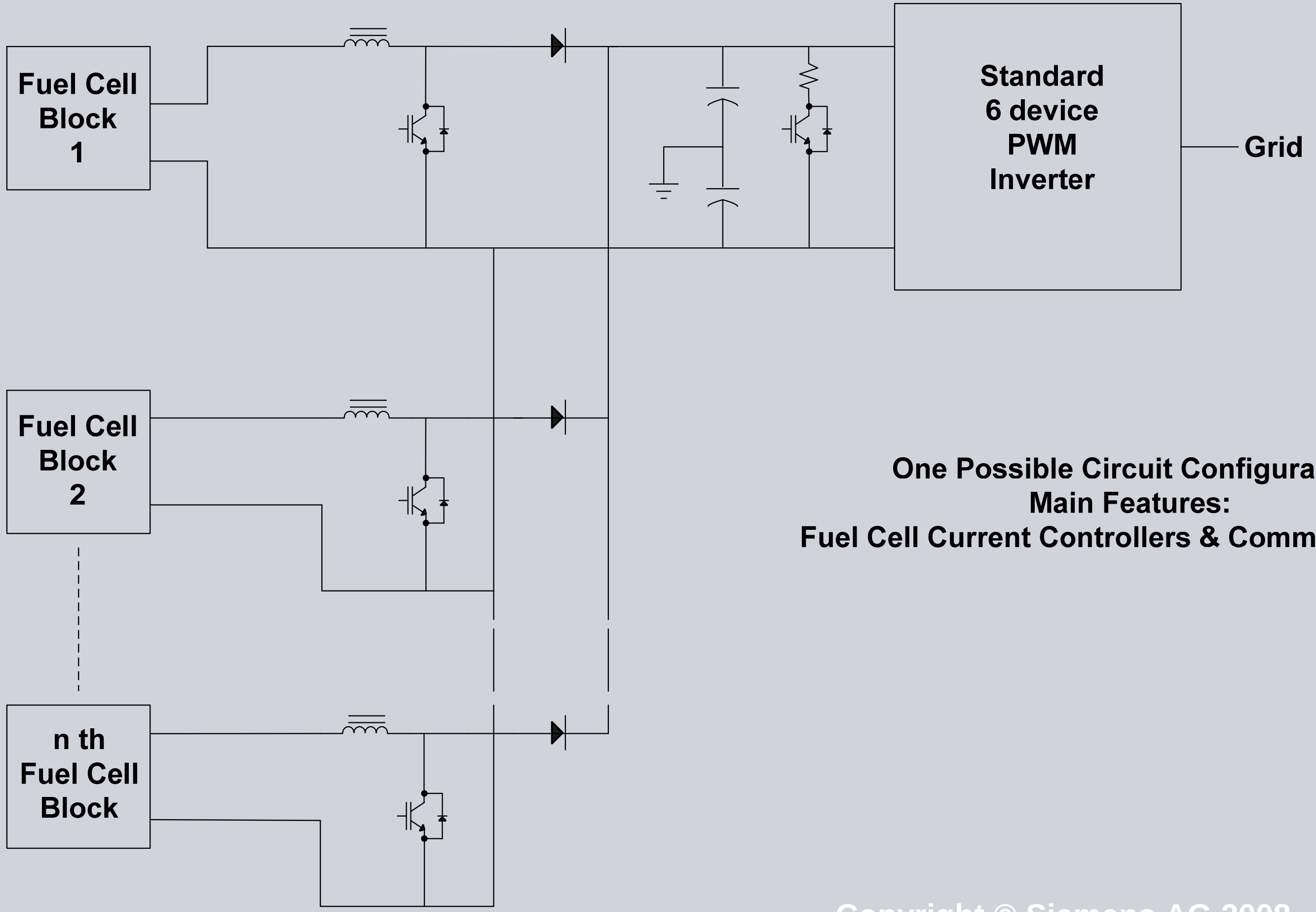
Modularity and Power Consolidation

SIEMENS

- Both bottom up (load control) and top down (aggregate power rating & delivery) perspectives are needed for selection of a low cost high megawatt PCS topology and system design
- The load control building block at the fuel cell module level must be highly cost optimized since it will repeat many times
- Power consolidation strategies need to support the necessary modularity
- Converter $/kW targets include and must be assessed on the complete network … the complete consolidation network must be evaluated. And the complete consolidation network design plan must influence how the fuel cells are individually loaded.

Power Consolidation Example 1
DC Choppers

Array of DC to DC
Chopper Converters

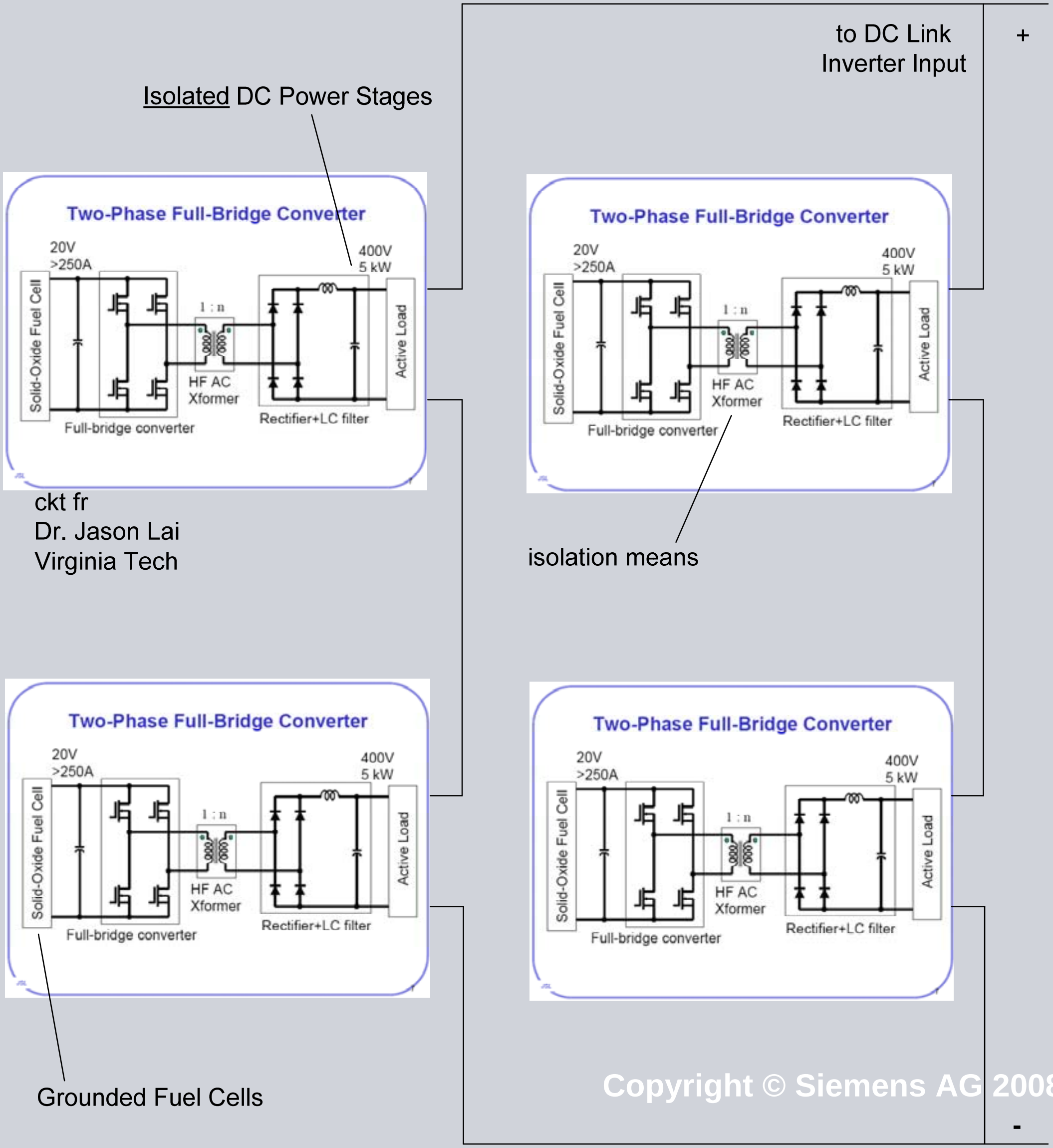


One Possible Circuit Configuration
Main Features:
Fuel Cell Current Controllers & Common DC Link

Power Consolidation Example 2
DC to DC Converters

Array of DC to DC Isolated Converters

2 x 2 shown
n x p capable



Isolated DC Power Stages

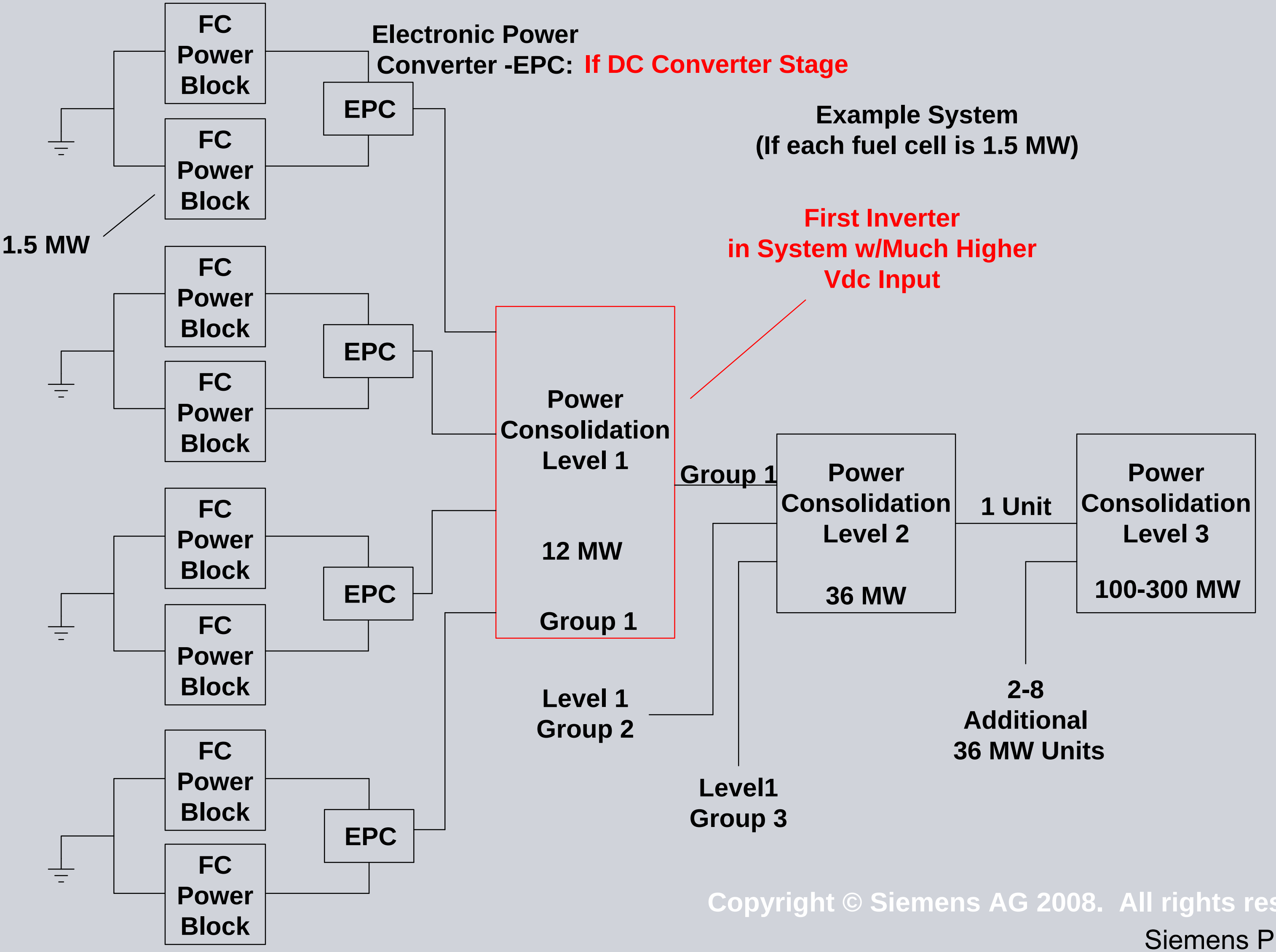
to DC Link
Inverter Input

ckt fr
Dr. Jason Lai
Virginia Tech

isolation means

Grounded Fuel Cells

Consolidation Concept & System Power Buildup



Alternative Strategy to Aggregate Power

The previous slides suggest the modular EPC (electronic power converter) to load the fuel cell has a high kVA rating equal to the level of the fuel cell power block … 0.5 to 2.0 MW

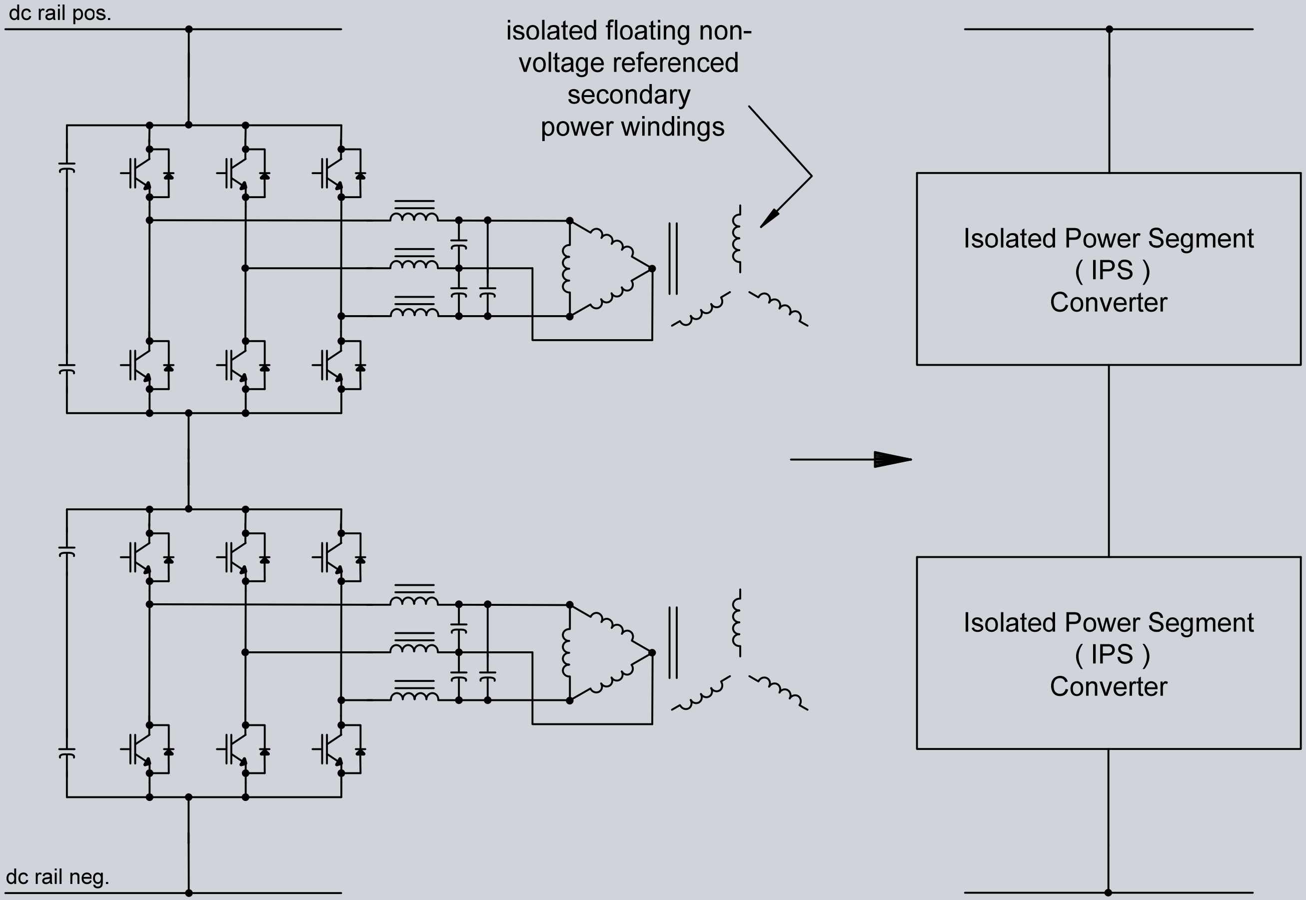
Next 2 slides take a different tack for the EPC loading device

Power Consolidation Example 3

Premise: several low-voltage drives are less expensive than one medium-voltage drive of equal total rating

cascaded multi-cell multi-level design

from a concept by
D.A. Derek
Mesta Electronics

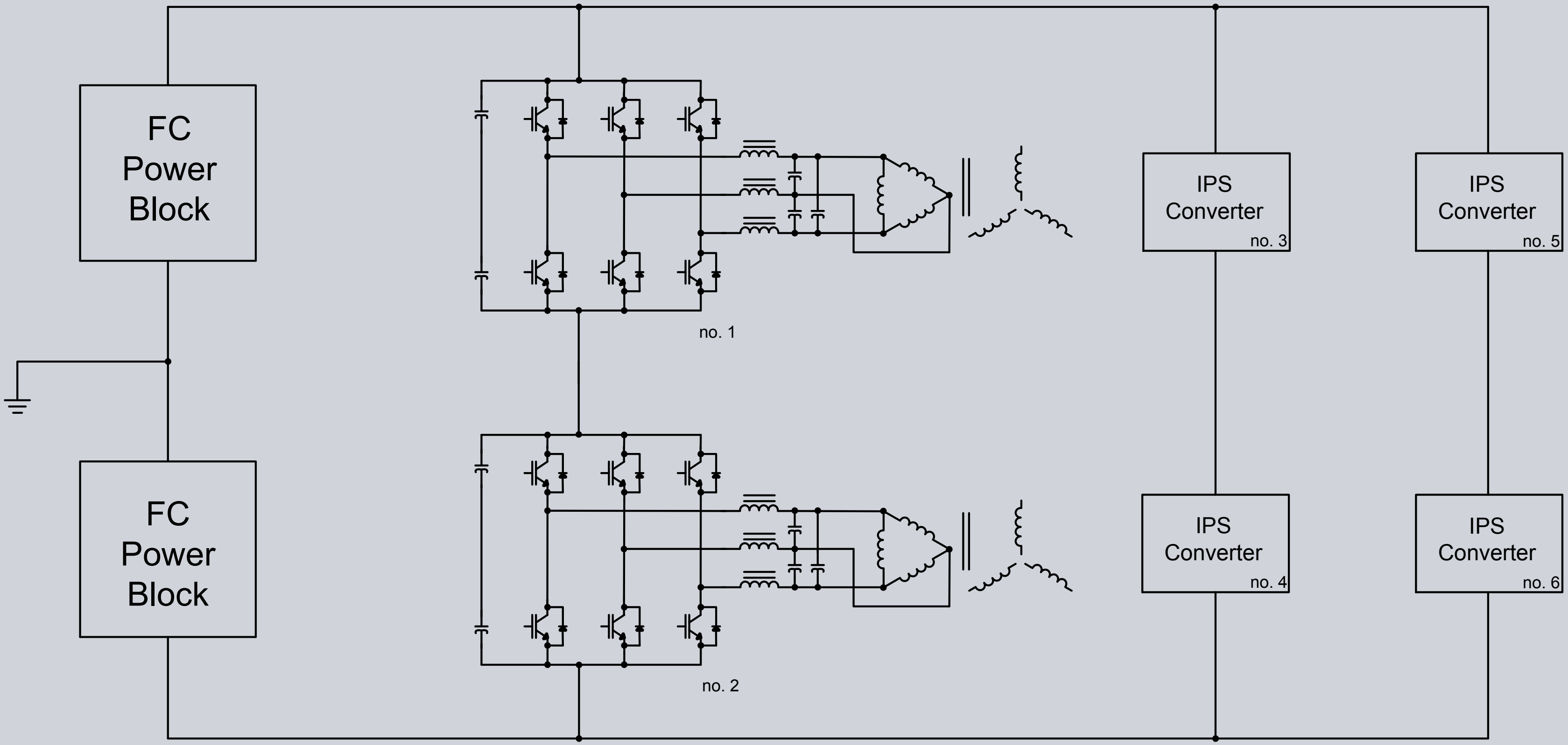


isolated floating non-voltage referenced secondary power windings

Isolated Power Segment
(IPS)
Converter

Isolated Power Segment
(IPS)
Converter

Power Consolidation Example 3

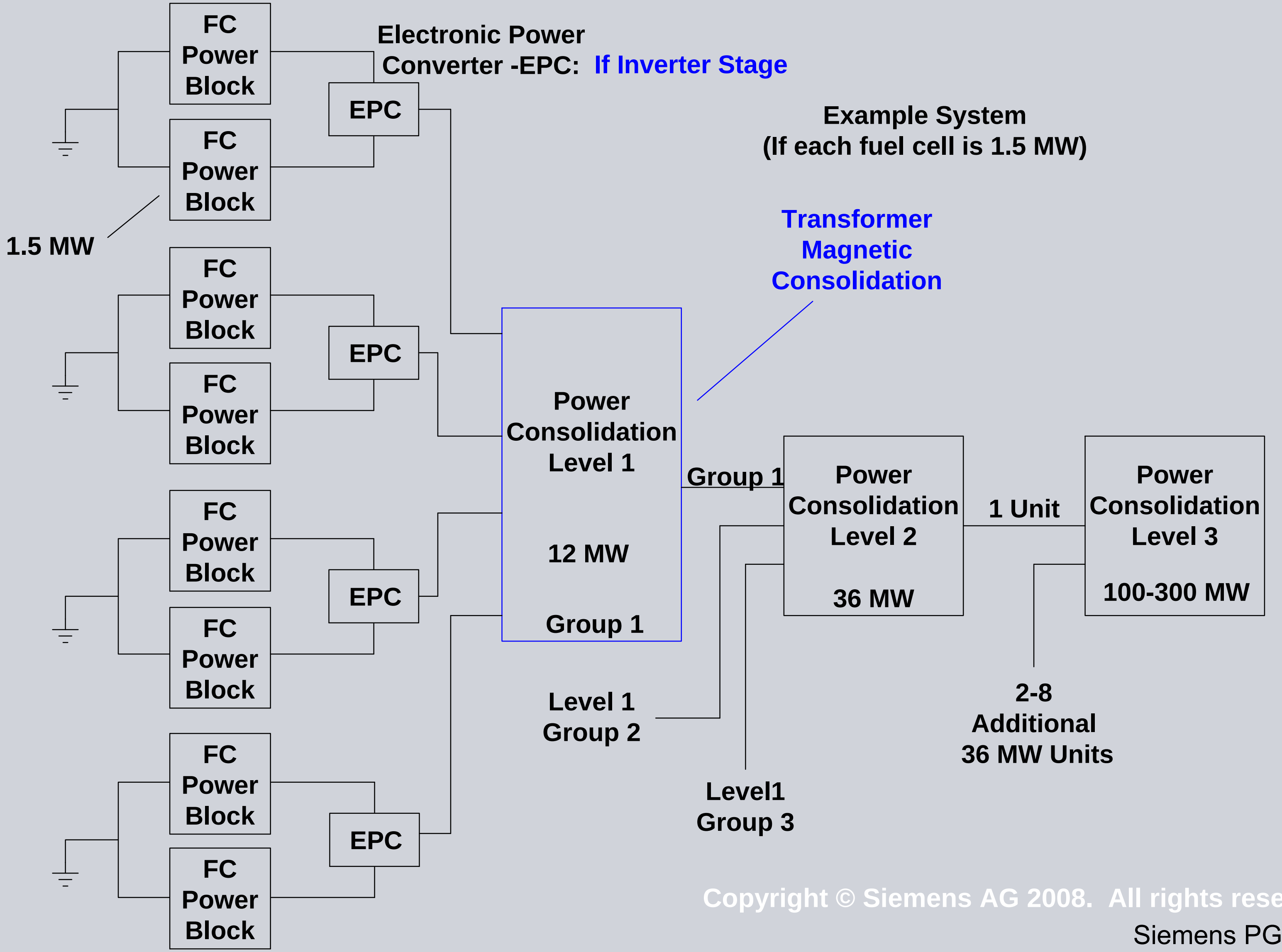


Array of DC to AC
Isolated Converters

2 x 3 shown
n x p capable

Secondary phase wndgs. in series for ac voltage
Parallel IPS converter legs for dc current

Consolidation Concept & System Power Buildup



Conclusions:

A design plan for a power circuit network (100-300 MW) is vital. The network must easily aggregate small power blocks and consolidate them into larger electrical sources.

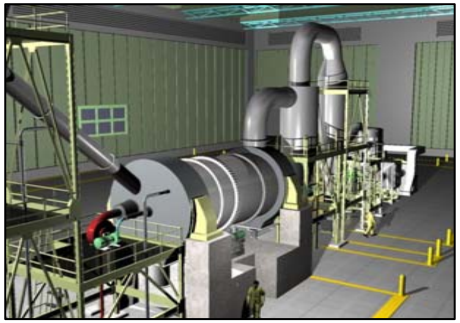
Key to all this working well is a set of effective methods to appropriately combine the electrical power drawn from all the relatively small units and then present it to the grid as one generation source.

U.S. Army Requirements-Driven Remote Power and Microgrid Opportunities

Distributed Generation

H_2 Generation & Storage

Waste to Energy



Remote Power

Franklin H. Holcomb

U.S. Army Engineer Research
and Development Center

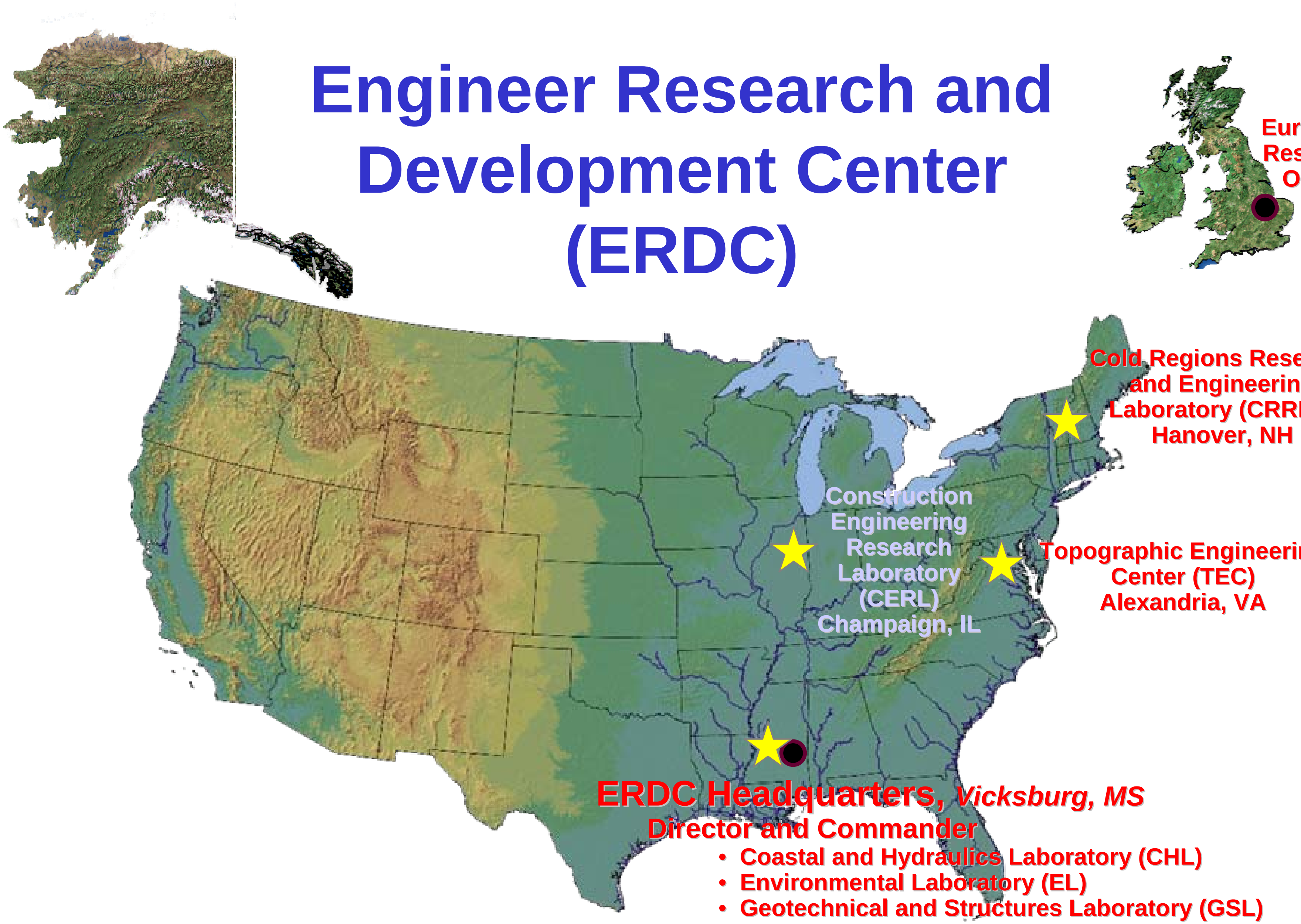
08 APR 08

Ph. (217) 373-5864
franklin.holcomb@us.army.mil

Presentation Outline

- Introduction
- Background
- Goals and Requirements
  - Installation
  - Warfighter
- Army Funded Activities
- Acknowledgements

Engineer Research and Development Center (ERDC)



European Research Office

Cold Regions Research and Engineering Laboratory (CRREL)
Hanover, NH

Construction Engineering Research Laboratory (CERL)
Champaign, IL

Topographic Engineering Center (TEC)
Alexandria, VA

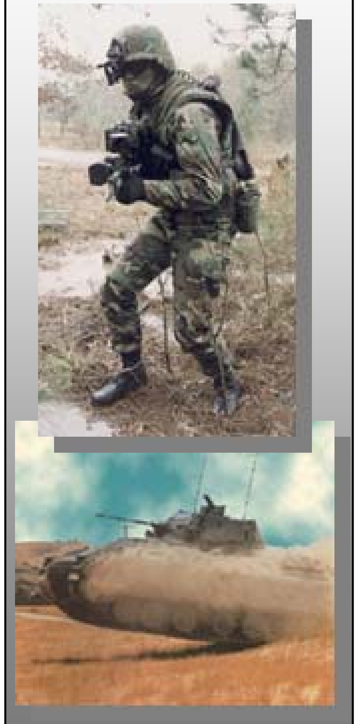
ERDC Headquarters, ***Vicksburg, MS***
Director and Commander

- **Coastal and Hydraulics Laboratory (CHL)**
- **Environmental Laboratory (EL)**
- **Geotechnical and Structures Laboratory (GSL)**
- **Information Technology Laboratory (ITL)**

Soldiers, Families, and Civilians

Home to the Force

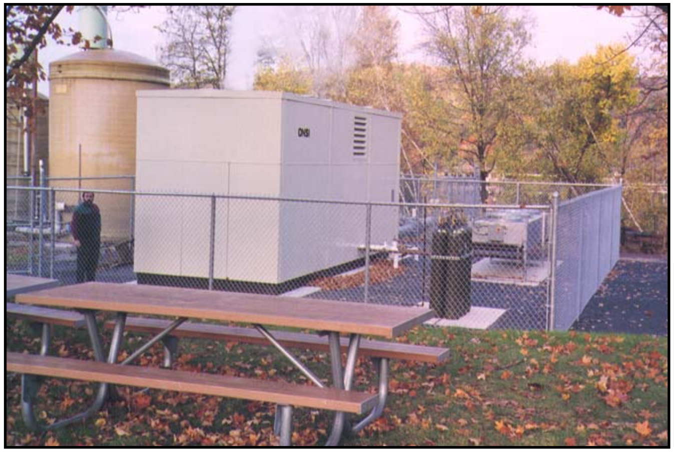
Power Projection



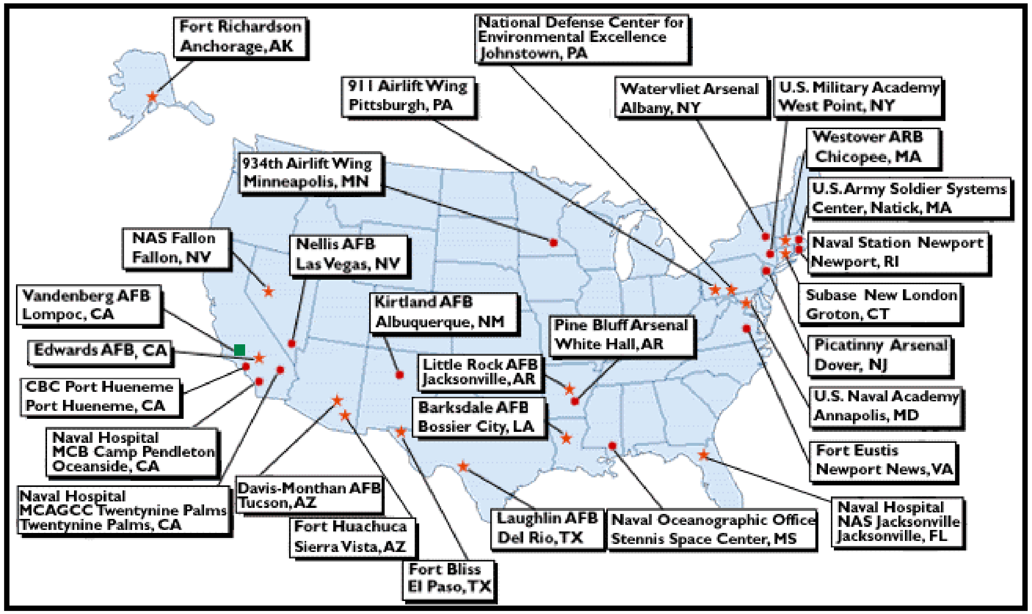
Work & Training

… are our Customers!

Fuel Cell Demonstrations at Military Sites

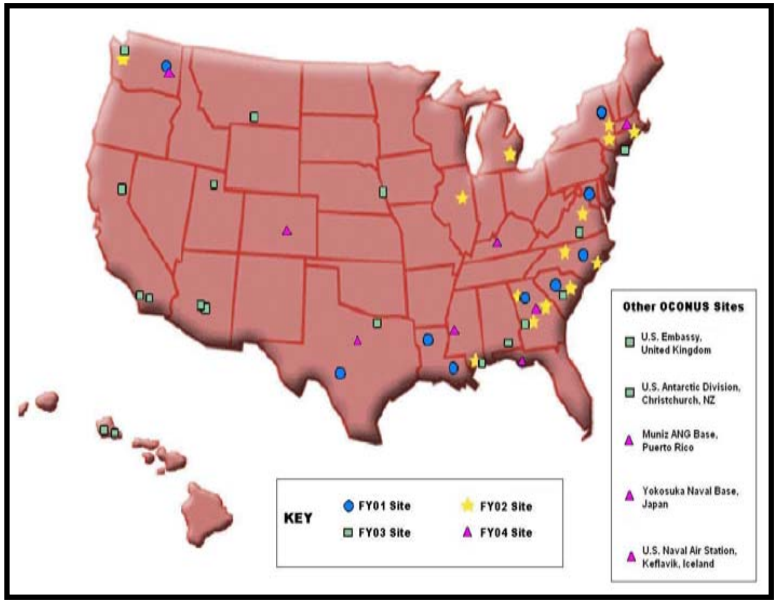


30 Fuel Cells
30 Sites
1 Manufacturer



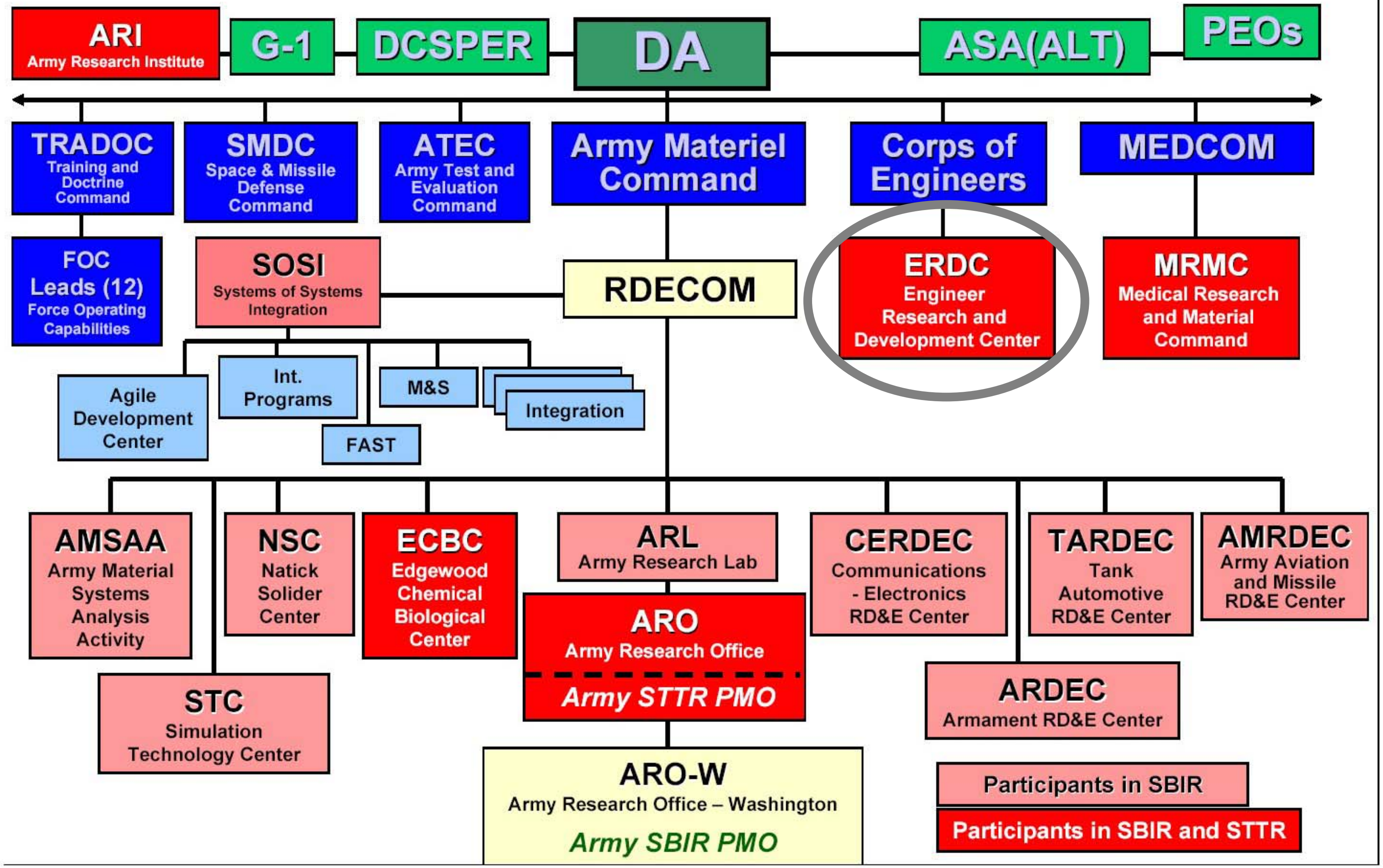
FY93-FY94 Phosphoric Acid Fuel Cell (PAFC) Project Sites

91 Fuel Cells
56 Sites
5 Manufacturers



FY01-FY04 Residential Proton Exchange Membrane Fuel Cell (PEMFC) Project Sites

ARMY R&D Organizations



ARI
Army Research Institute

G-1

DCSPER

DA

ASA(ALT)

PEOs

TRADOC
Training and Doctrine Command

SMDC
Space & Missile Defense Command

ATEC
Army Test and Evaluation Command

Army Materiel Command

Corps of Engineers

MEDCOM

FOC Leads (12)
Force Operating Capabilities

SOSI
Systems of Systems Integration

RDECOM

ERDC
Engineer Research and Development Center

MRMC
Medical Research and Material Command

Agile Development Center

Int. Programs

M&S

Integration

FAST

AMSAA
Army Material Systems Analysis Activity

NSC
Natick Solider Center

ECBC
Edgewood Chemical Biological Center

ARL
Army Research Lab

ARO
Army Research Office

Army STTR PMO

CERDEC
Communications - Electronics RD&E Center

TARDEC
Tank Automotive RD&E Center

AMRDEC
Army Aviation and Missile RD&E Center

STC
Simulation Technology Center

ARDEC
Armament RD&E Center

ARO-W
Army Research Office – Washington

Army SBIR PMO

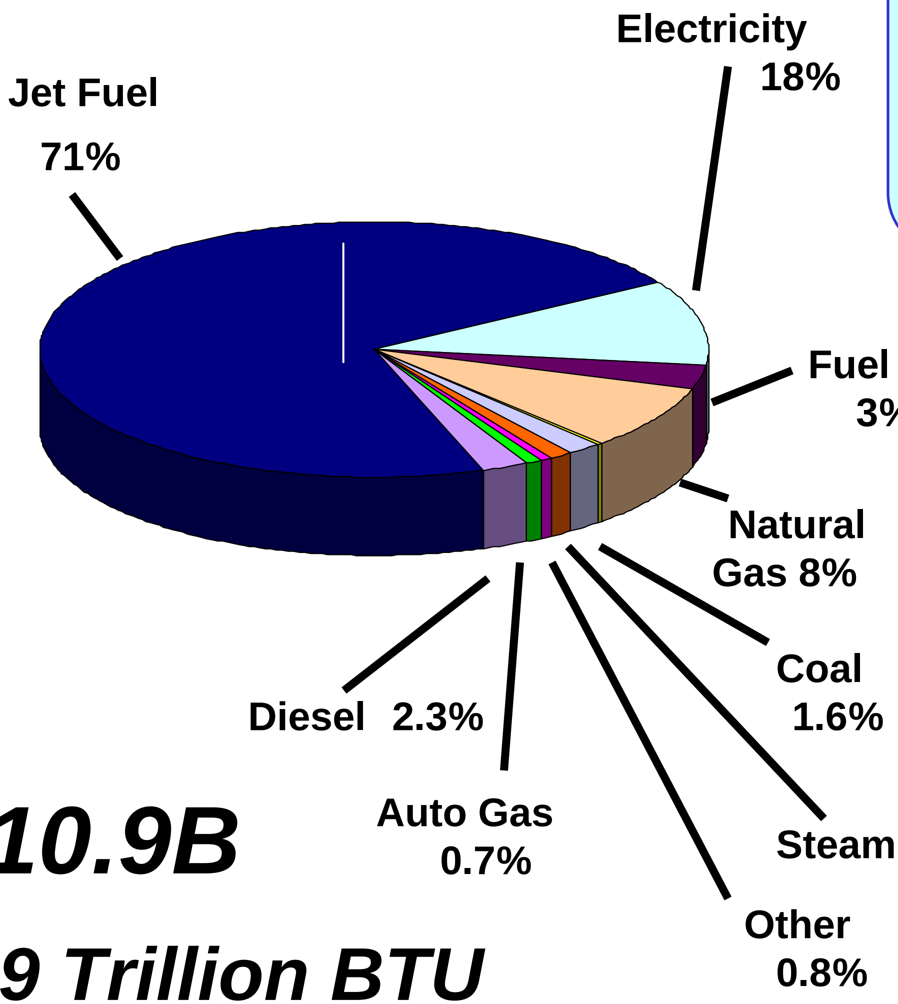
🟥 Participants in SBIR

🟥 Participants in SBIR and STTR

FY05 DoD Energy Use

Total Site-delivered Energy (BTU)

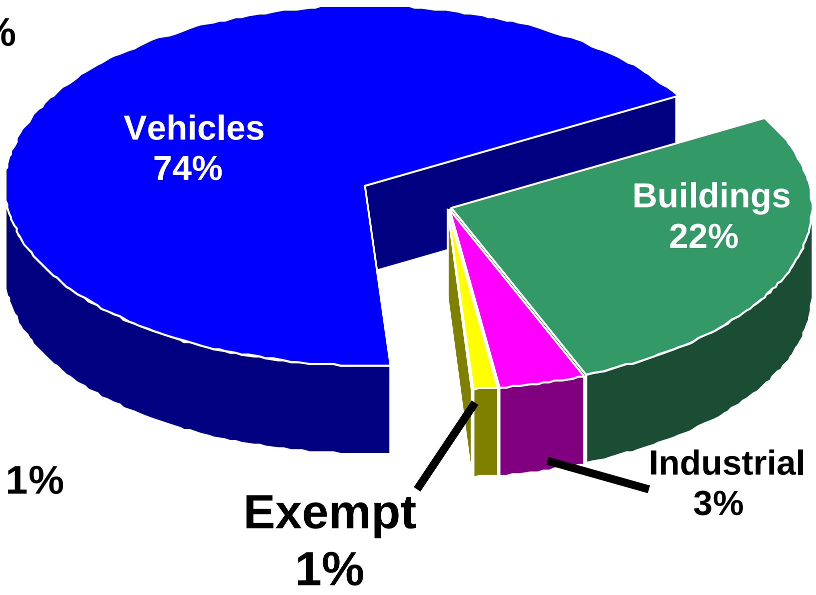
Commodity



Nation’s single largest energy user

(1% of total U.S. energy use & 78% of Federal energy use)

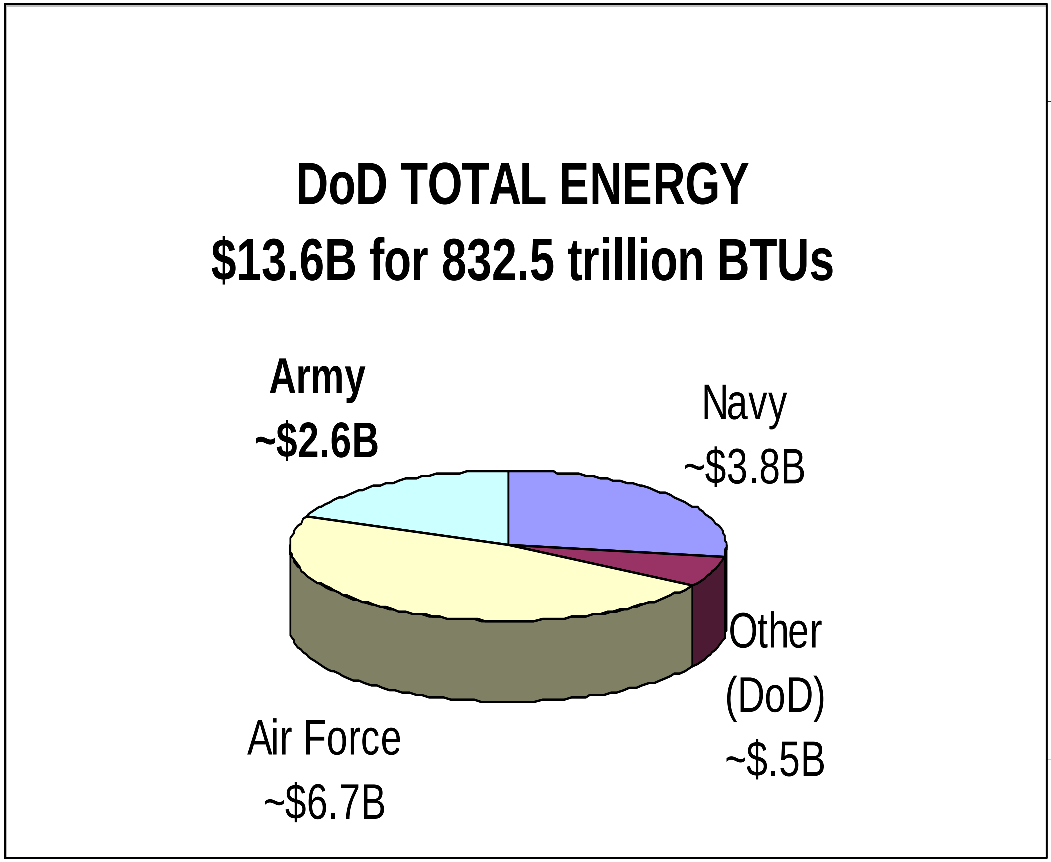
Application

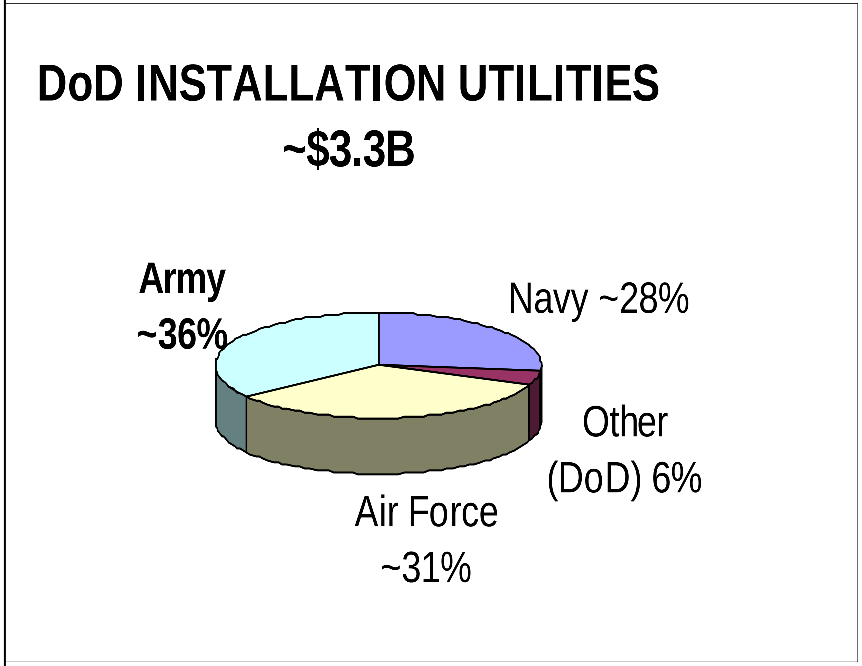


$10.9B

919 Trillion BTU

FY06 DoD Energy Consumption


DoD TOTAL ENERGY
$13.6B for 832.5 trillion BTUs


DoD INSTALLATION UTILITIES
~$3.3B

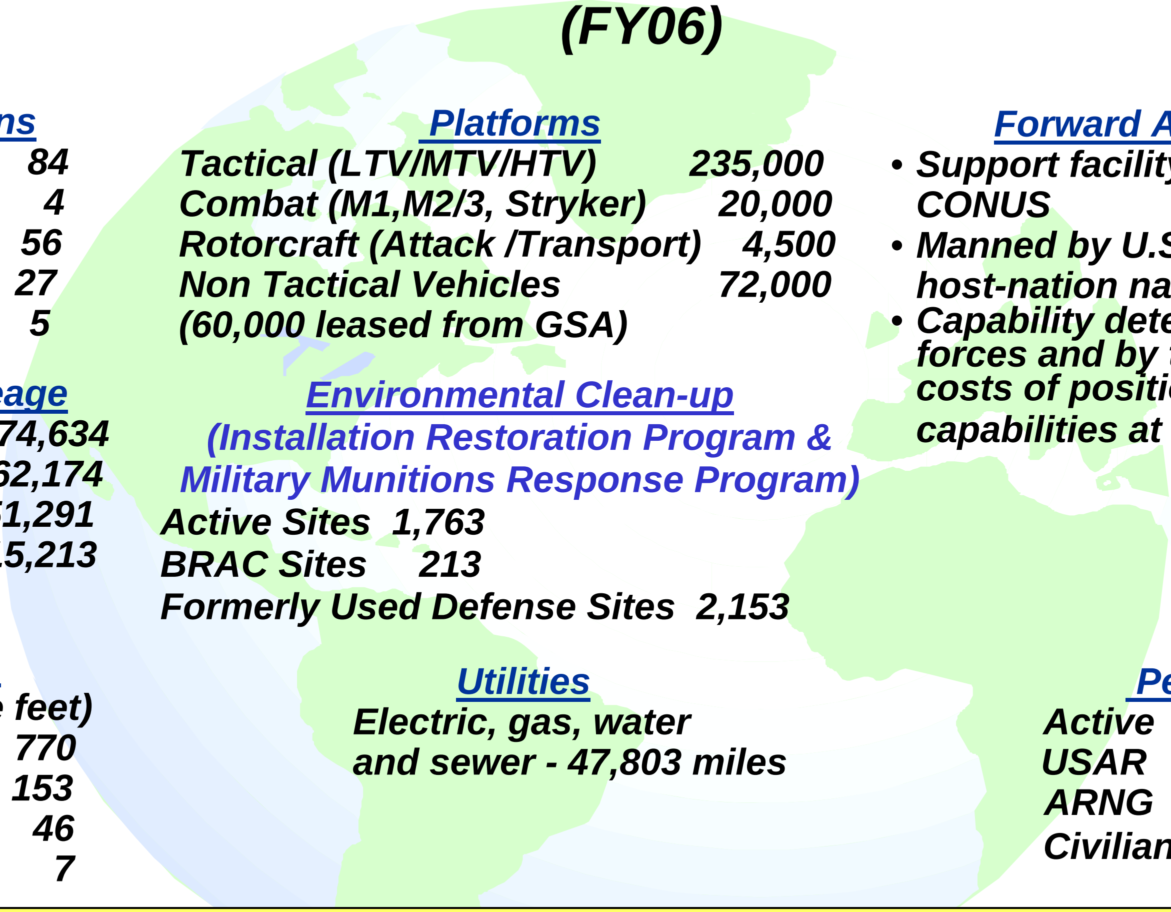
The Army represents approximately:

- ***19% of DoD Energy consumption***
- ***14% of DoD Fuel consumption***
- ***36% of DoD Utility consumption***

Army Universe

Scope for Power and Energy Considerations

(FY06)



Installations

IMCOM	*84*
Reserves	*4*
National Guard	*56*
AMC	*27*
Other	*5*

Land Acreage

United States	*15,174,634*
Europe	*162,174*
Asia	*51,291*
Other Overseas	*15,213*

Buildings

(million square feet)

United States	*770*
Europe	*153*
Asia	*46*
Other	*7*

Platforms

Tactical (LTV/MTV/HTV)	*235,000*
Combat (M1,M2/3, Stryker)	*20,000*
Rotorcraft (Attack /Transport)	*4,500*
Non Tactical Vehicles	*72,000*
(60,000 leased from GSA)	

Environmental Clean-up

(Installation Restoration Program & Military Munitions Response Program)

Active Sites	*1,763*
BRAC Sites	*213*
Formerly Used Defense Sites	*2,153*

Utilities

Electric, gas, water and sewer - 47,803 miles

Forward Area Bases

- *Support facility outside of CONUS*
- *Manned by U.S. military or host-nation nationals*
- *Capability determined by the forces and by the risks and costs of positioning specific capabilities at its location.*

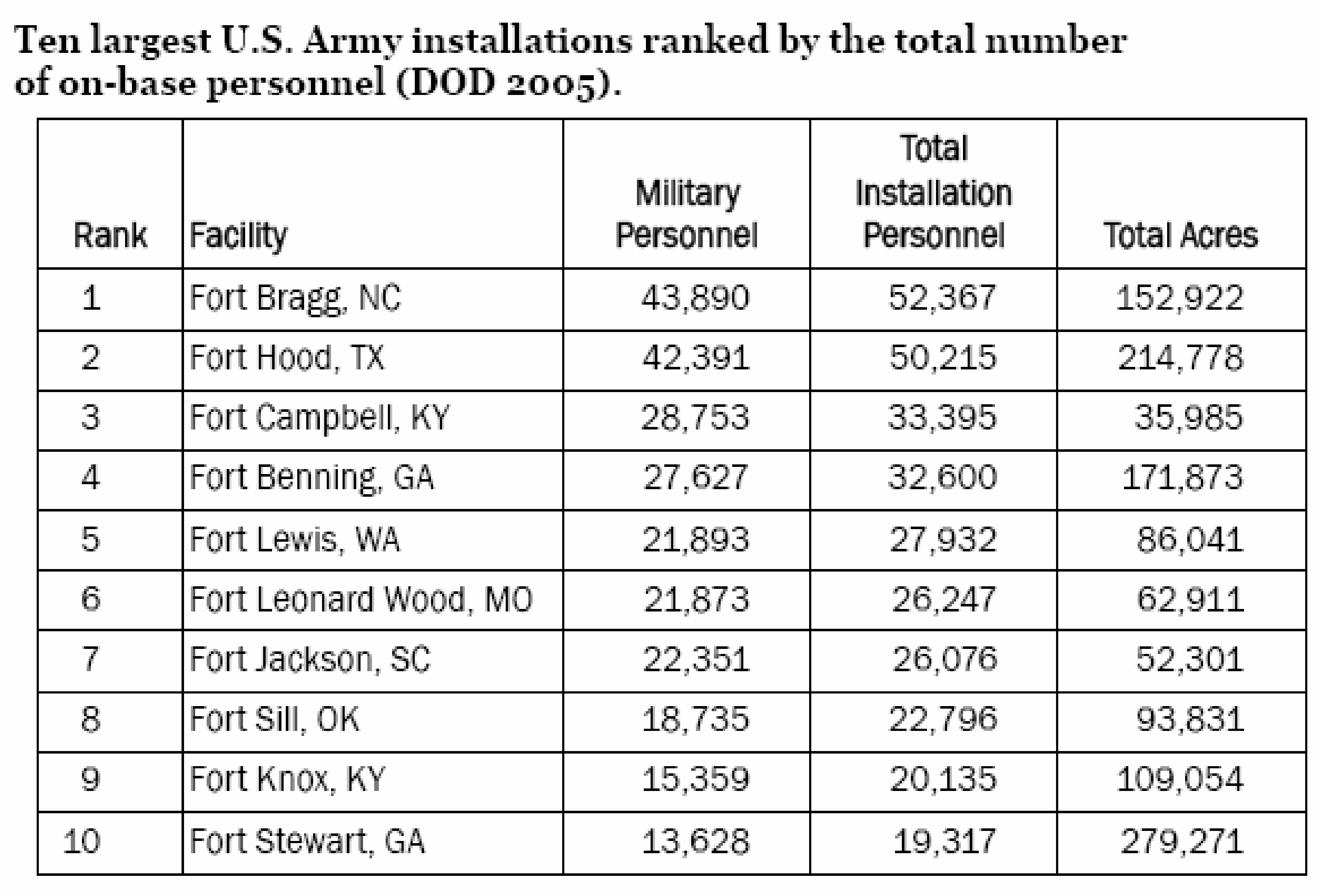
People

Active	*482,400*
USAR	*205,000*
ARNG	*350,000*
Civilians	*229,000*

FY06 Army fuel and utility consumption:

- *412 M gallons of jet and multi-purpose mobility fuel at cost of $940 M*
- *59 M gallons of diesel at cost of $123 M*
- *20 M gallons of gasoline at cost of $45 M*
- *330,000 gallons of biodiesel fuel at cost of $775 K*
- *$1.211 B annual utility cost for 77.3 BBtu*

as of 30 Sep 05



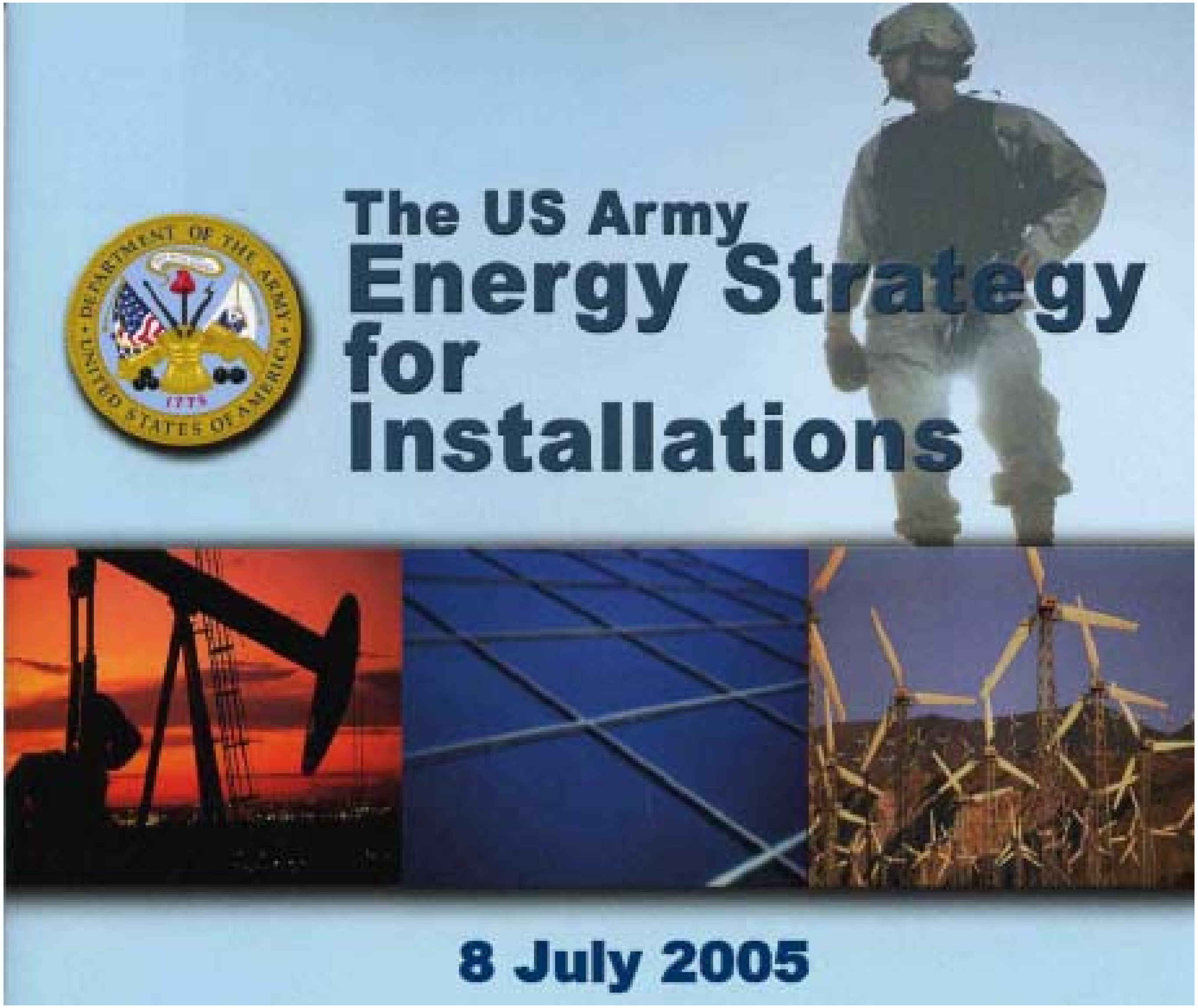
Ten largest U.S. Army installations ranked by the total number of on-base personnel (DOD 2005).

Rank	Facility	Military Personnel	Total Installation Personnel	Total Acres
1	Fort Bragg, NC	43,890	52,367	152,922
2	Fort Hood, TX	42,391	50,215	214,778
3	Fort Campbell, KY	28,753	33,395	35,985
4	Fort Benning, GA	27,627	32,600	171,873
5	Fort Lewis, WA	21,893	27,932	86,041
6	Fort Leonard Wood, MO	21,873	26,247	62,911
7	Fort Jackson, SC	22,351	26,076	52,301
8	Fort Sill, OK	18,735	22,796	93,831
9	Fort Knox, KY	15,359	20,135	109,054
10	Fort Stewart, GA	13,628	19,317	279,271

Rank	Facility	Average Annual Demand	Summer Peak Electricity Demand	Minimum Demand	Peak kW/ Base person	Annual Average/ Summer Peak
1	Fort Bragg, NC		100-110 MW peak going to 150 MW		2.01	
2	Fort Hood, TX		99 MW		1.98	
3	Fort Campbell, KY	~30 MW	48-56 MW (32-38 MW winter peak)		1.56	0.58
4	Fort Benning, GA					
5	Fort Lewis, WA	27 MW	36 MW		1.29	0.75
6	Fort Leonard Wood, MO					
7	Fort Jackson, SC	~ 20 MW	31 MW summer peak, 23 MW winter peak		1.18	0.64
8	Fort Sill, OK	19.4 MW	36 MW	8-10 MW winter night	1.58	0.54
9	Fort Knox, KY		22.36 MW		1.09	
10	Fort Stewart, GA					
Averages					*1.53*	*0.60*

Goals and Requirements

- ✓ 2005 Army Energy and Water Campaign Plan
- ✓ 2005 Energy Policy Act
- 2006 TRADOC Pamphlet 525-66,
  - FOC-09-03: Power & Energy
  - FOC-08-04: Installations as our Flagships
- 2007 Executive Order 13423
- ✓ 2007 SERDP SON for Scalable Power Grids
- ✓ 2006/2007 Defense Science Board Key Facility Energy Strategy Recommendations



The US Army
Energy Strategy
for
Installations

8 July 2005

http://army-energy.hdqa.pentagon.mil

Army Energy Strategy for Installations

- **The 2005 Strategy sets the general direction for the Army in five major initiatives:**
  - ***Eliminate energy waste in existing facilities***
  - ***Increase energy efficiency in new construction and renovations***
  - ***Reduce dependence on fossil fuels***
  - ***Conserve water resources***
  - ***Improve energy security***

What is Energy Security?

Utility Reliability?

- Energy security is the capacity to avoid adverse impact of energy disruptions caused either by natural, accidental or intentional events affecting energy and utility supply and distribution systems.

Energy Policy Act of 2005

- **Effective on August 8, 2005**

- **Federal Facilities Provisions**
  - **Energy Reduction Goals - 20% by FY 2015**
  - **Energy Efficient Buildings - 30% better than ASHRAE standards**
  - **Renewable Energy – Purchase 7.5% or more in 2013 and beyond (DoD Internal Policy is 25% by 2025)**
  - **Energy Efficient Products – Install Energy Star or FEMP designated products**

2007 Strategic Environmental Research and Development Program (SERDP) Statement of Need (SON) for Scalable Power Grids

- The Objective of this SON is to Provide DoD Installations with the Capability to Network Distributed Generation (DG) Technologies, Including Renewables, Especially at Mission Critical Facilities.

- Requirements
  - Robust Network Topology Dynamics
  - Dynamic Response of Distributed Control Strategies
  - Mission-Based Load Shedding and Algorithms
  - Conduct Simulation-Based Microgrid Experiments

2006/2007 Defense Science Board Key Facility Energy Strategy Recommendations

- **Released February 2008**
- **Recommendation #2: Reduce the Risk to Critical Missions at Fixed Installations from Loss of Commercial Power and Other Critical National Infrastructure.**
  - **Develop a plan to "Island Critical Missions from the Grid by December 2008**
  - **Require that all DoD Installations Meet a "Net Zero" Energy Standard by 2025**

$ / Gallon of Delivered Fuel to Battlefield

$ 10 – Truck Convoy Driven from Kuwait

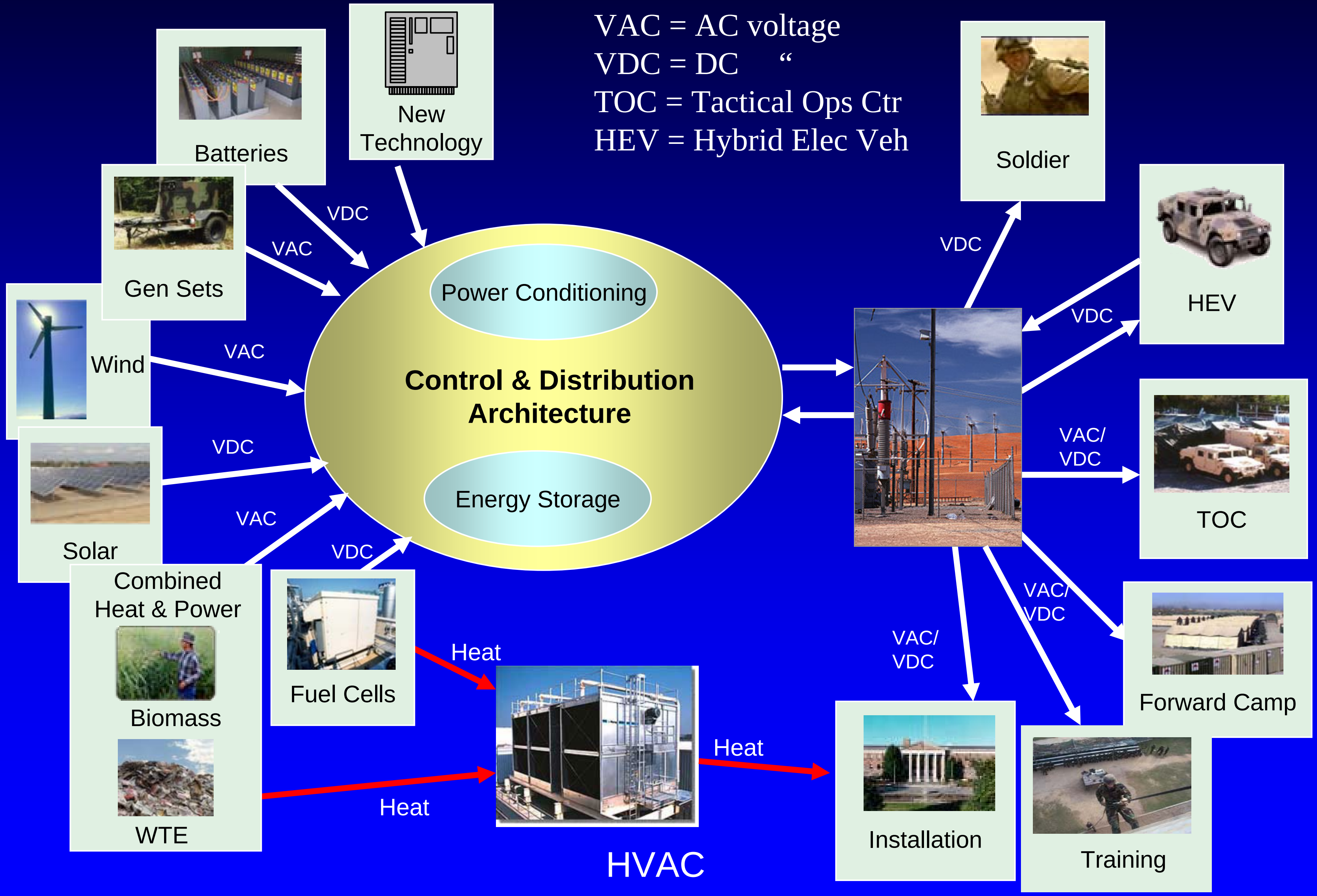
$ 40 – Cargo Ship from Overseas

$ 400 – Flown in Via Aircraft

$$ What Cost in Lives ??

How Do We Get There?

To be successful, the Army Campaign Objectives need a Full-Spectrum Power Architecture … microgrid concept



VAC = AC voltage
VDC = DC   “
TOC = Tactical Ops Ctr
HEV = Hybrid Elec Veh

Batteries
New Technology
Gen Sets
Wind
Solar
Combined Heat & Power
Biomass
WTE
Fuel Cells
VDC
VAC
VAC
VDC
VAC
VDC

Control & Distribution Architecture

Power Conditioning

Energy Storage

Heat
Heat
Heat

HVAC

Soldier
HEV
TOC
Forward Camp
Training
Installation
VDC
VDC
VAC/ VDC
VAC/ VDC
VAC/ VDC

U.S. ARMY

RDECOM

MOBILE ELECTRIC POWER
DEPARTMENT OF DEFENSE

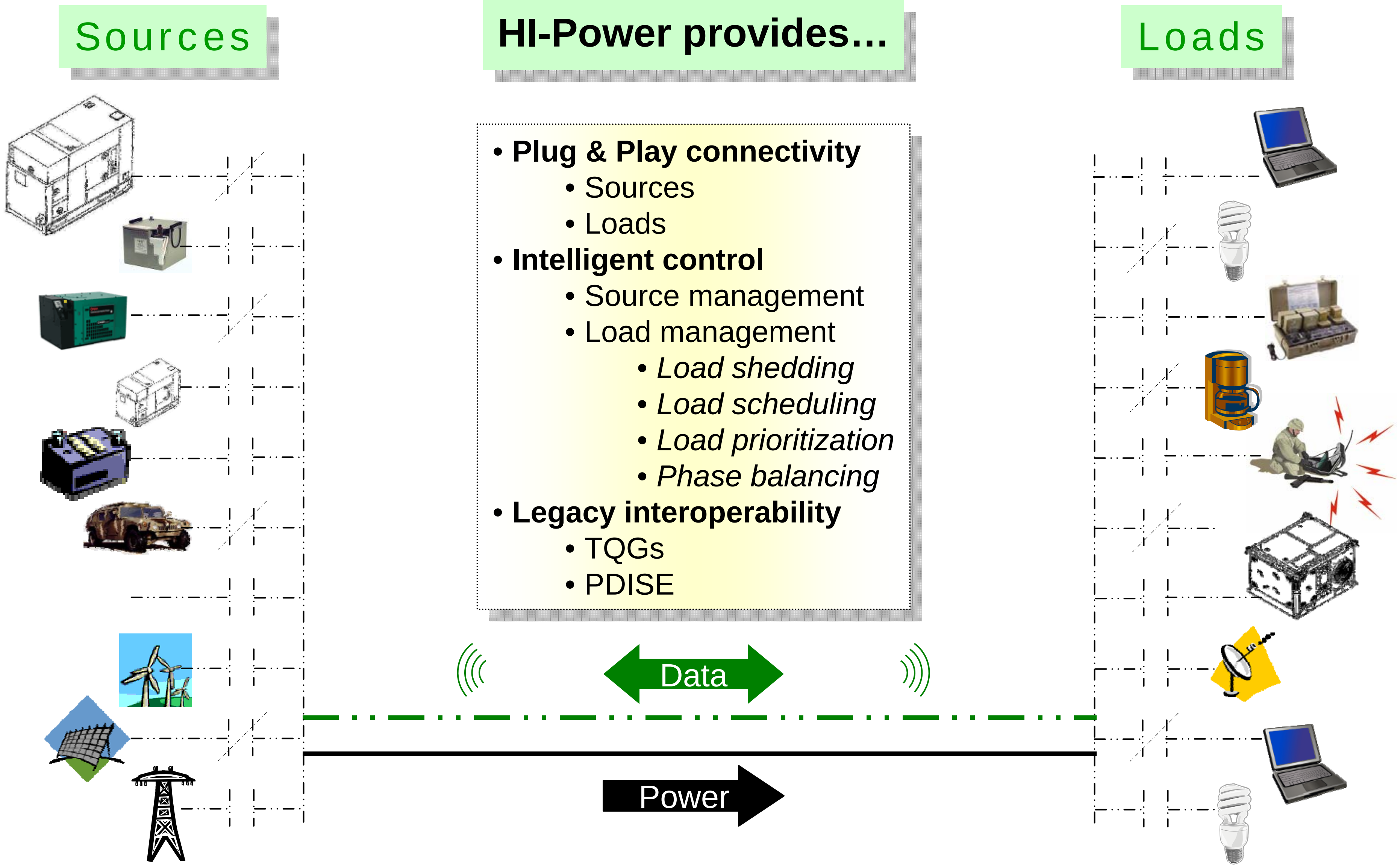
CERDEC
US ARMY – RDECOM

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Hybrid-**I**ntelligent POWER

“HI-POWER”

HI-Power Concept



Sources

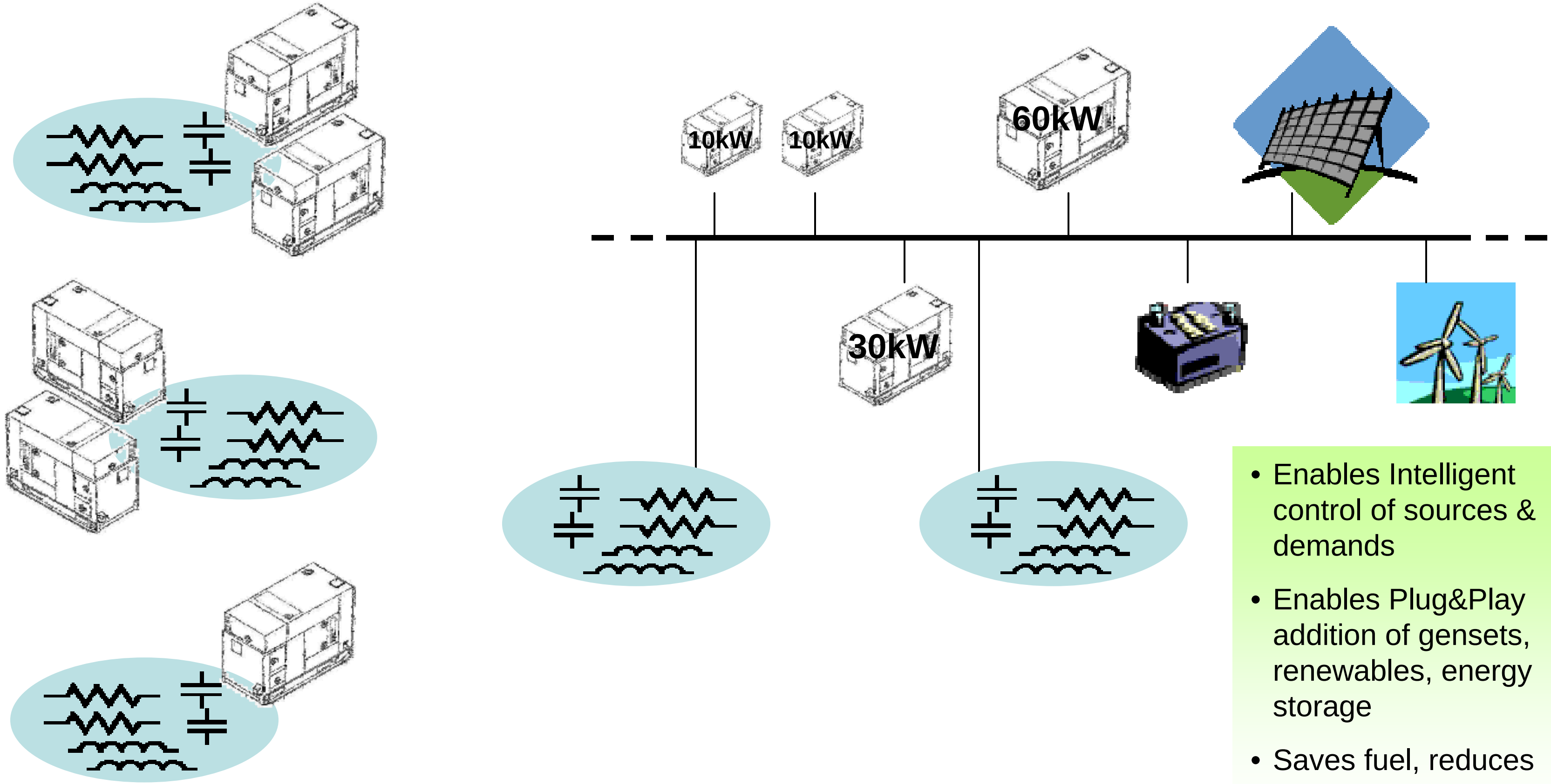
HI-Power provides…

- **Plug & Play connectivity**
  - Sources
  - Loads
- **Intelligent control**
  - Source management
  - Load management
    - *Load shedding*
    - *Load scheduling*
    - *Load prioritization*
    - *Phase balancing*
- **Legacy interoperability**
  - TQGs
  - PDISE

Loads

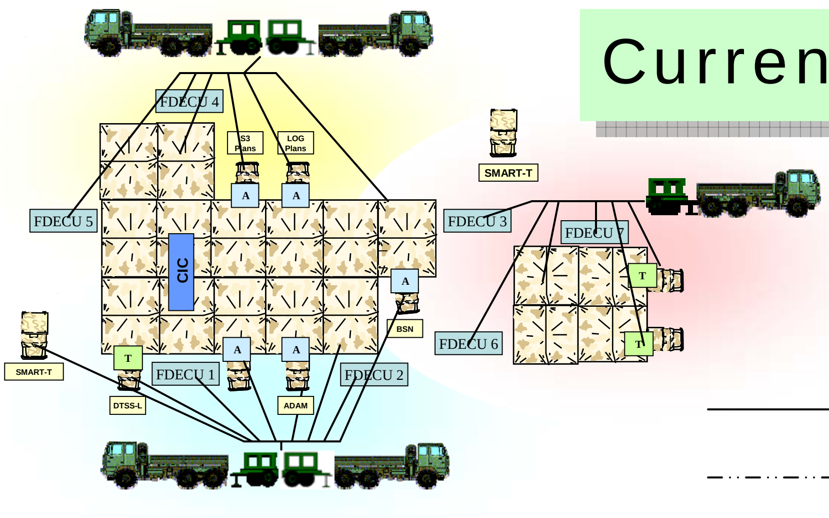
HI-Power Impact

Power Islands vs. Central Power Buss



- Enables Intelligent control of sources & demands
- Enables Plug&Play addition of gensets, renewables, energy storage
- Saves fuel, reduces cost, reduces emissions

Power for Stryker Brigade

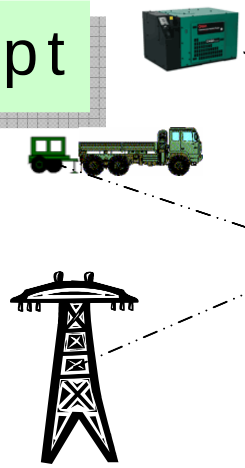


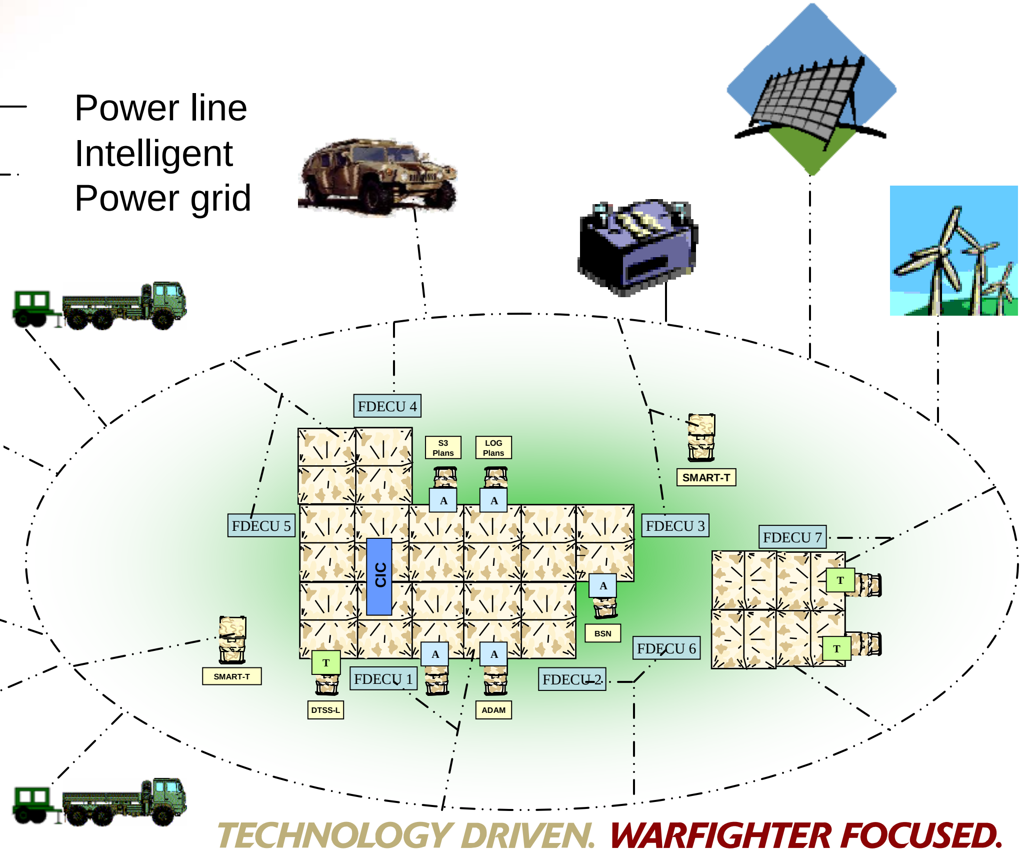
Current Situation

***No*…**
Power Grid
Intelligent distribution
Renewables
Energy Storage

Power line
Intelligent
Power grid

HI-Power Concept

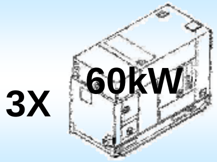
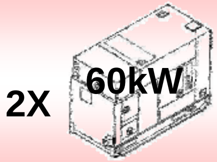
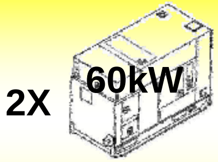
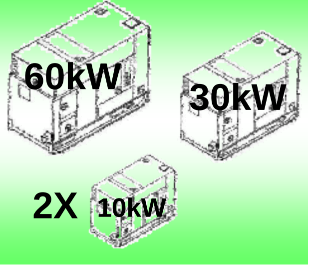




Direct / Indirect Benefits

- Power Production:
  - Fuel Savings
  - Cost Savings
  - Longer life (fewer operational hours per mission)
- Transportation:
  - Reduced # of Prime Movers
  - Potential for smaller, less-costly, more fuel-efficient Transport Vehicles
- Emissions:
  - Reduction is a by-product of lower fuel consumption
- Wide Applicability:
  - FOBs, Division-to-Battalion, Echelons above Division (EAD)
- Operational Benefits:
  - Lower Noise
  - Greater redundancy
  - Flexibility
  - Reduced O&S Costs
  - 24/7 Operational Capability
  - Smaller footprint
- Force Protection

Benefits of Establishing a Grid & Intelligent Control for Stryker

	Max Power Draw (kW)	Daily Fuel Usage (gal)	% savings	
• Current	96	162	-	
• Future (w/Grid)	96	139	14	
• Future (w/Grid & on/off Control)	96	134	17	
• Future (w/Grid, on/off Control, & Right-sizing)	96	129	20	

Example based on CERDEC Power Assessment of Stryker at Ft. Irwin, CA, and use of TEP ORD Mission Profile

Programmatics

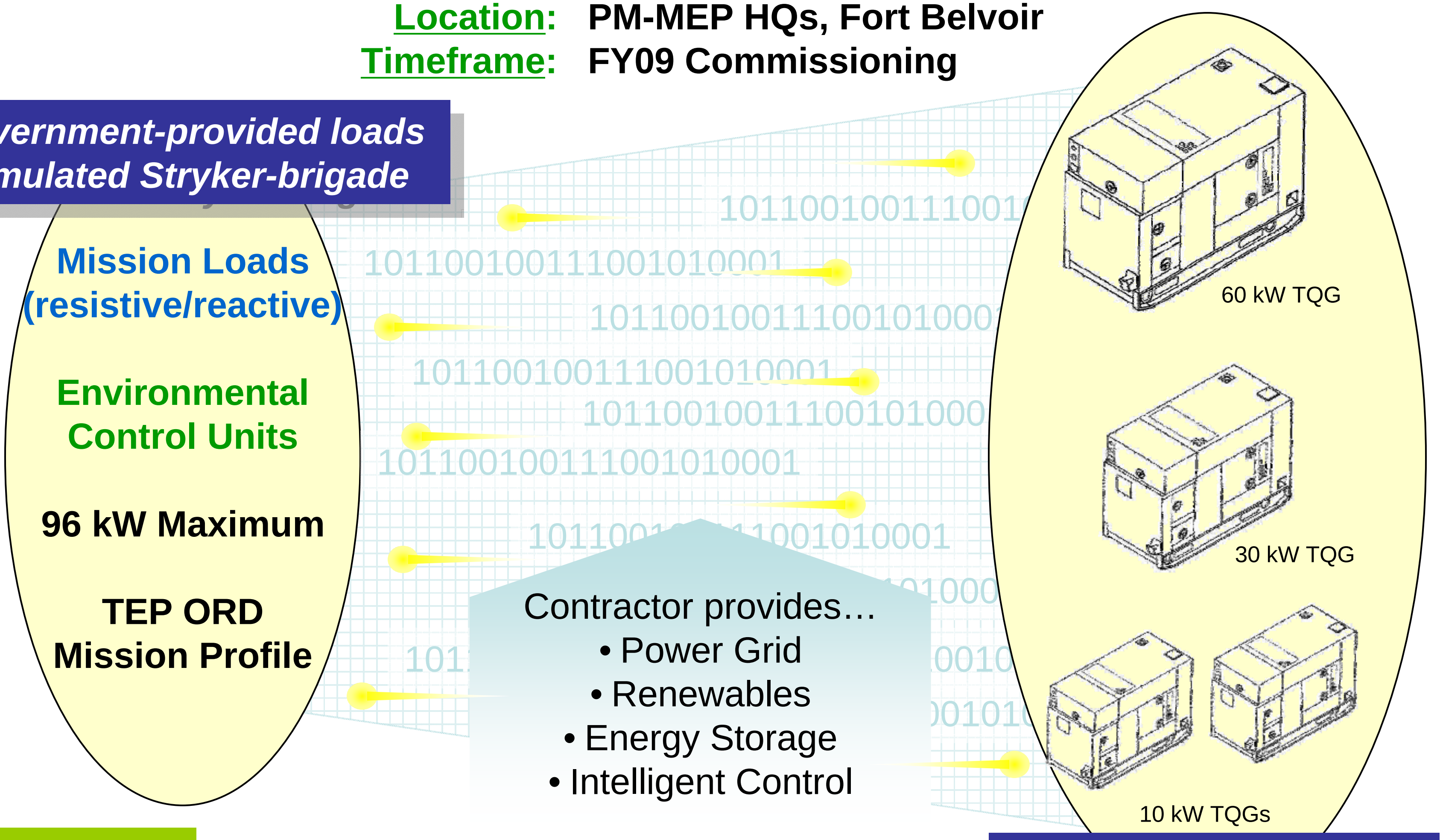
Funding Source:	OSD – DDR&E thru Agile Dev. Center
Management:	PM-MEP
Program Execution:	CERDEC
Funds:	6.3 R&D
Schedule:	6-year program FY08 – FY13

Program Status

HI-Power Industry Day	18 July 2007
Power Technology BAA	25 July 2007
White Papers received	1 Oct 2007
$ to NREL for HOMER upgrade	Nov 2007
White Paper Evals completed	Nov 2007
Request for Full Proposals	26 Dec 2007
Receive Full Proposals	8 Feb 2008
Multiple Contract Awards	March 2008

HI-Power Test Bed

Location: **PM-MEP HQs, Fort Belvoir**
Timeframe: **FY09 Commissioning**



Government-provided loads
Simulated Stryker-brigade

Mission Loads
(resistive/reactive)

Environmental
Control Units

96 kW Maximum

TEP ORD
Mission Profile

Contractor provides…
- Power Grid
- Renewables
- Energy Storage
- Intelligent Control

Government-provided
power sources

Measure…
- ***Fuel consumption***
- ***Performance***
- ***Size / Weight…***

HI-Power Vision

Power Grid

- Plug & Play architecture
- Multiple power sources
- Renewables
- Energy Storage

New Power Paradigm

- ✓ *Fuel savings*
- ✓ *Cost savings*
- ✓ *Force protection*
- ✓ *Flexible*
- ✓ *Adaptive*

Intelligent Control

- Phase balancing
- Load prioritization
- *Source* management
- *Demand* management

The NextEnergy Advanced Mobile Power & Energy Program

Briefing to

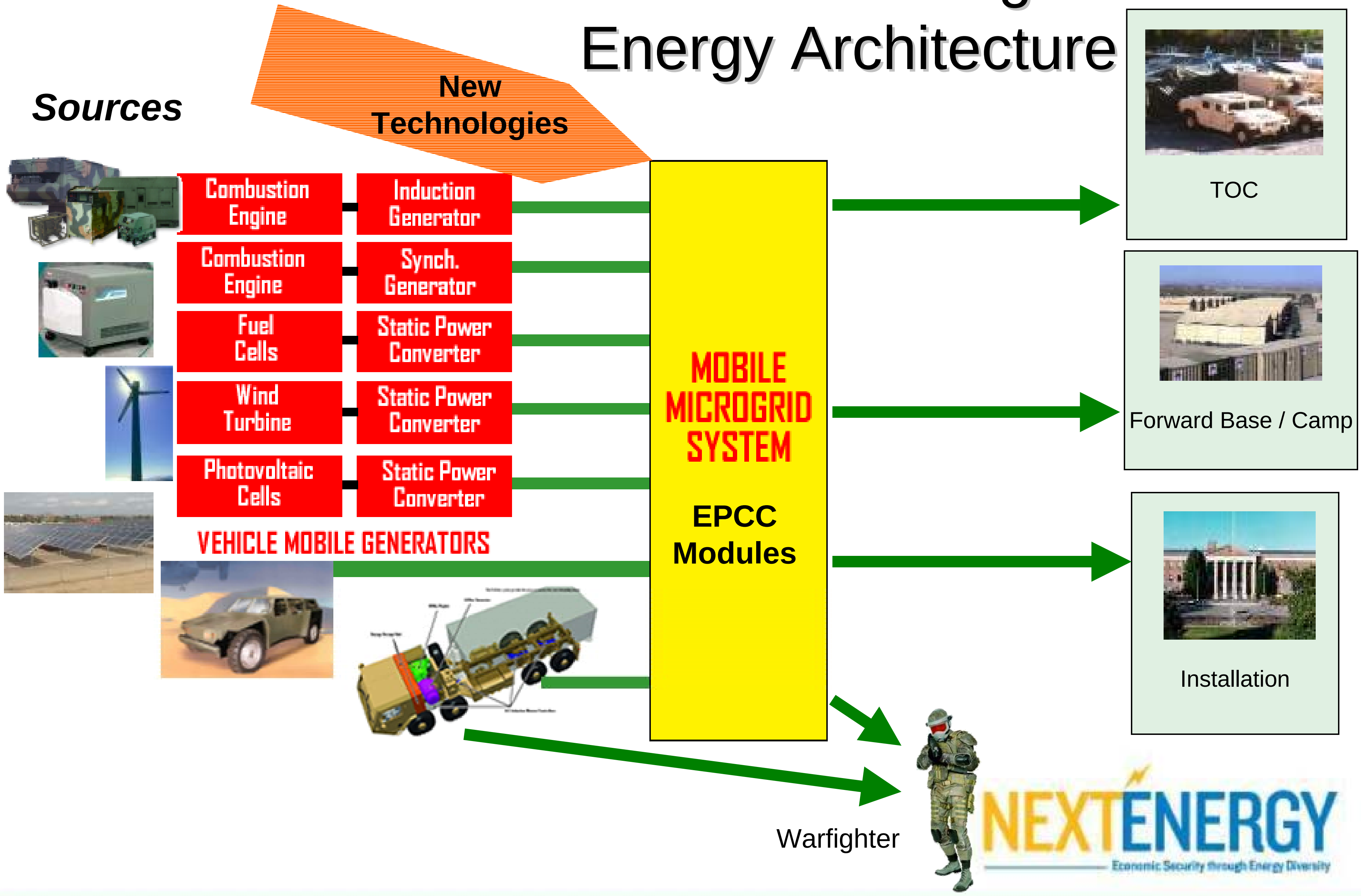
NRC: Achieving Cleaner Distributed Power Generation

In Remote Locations

David McLean - COO
March 11, 2008

www.NextEnergy.org

The Advanced Mobile Microgrid: Energy Architecture



Sources

New Technologies

Combustion Engine — Induction Generator

Combustion Engine — Synch. Generator

Fuel Cells — Static Power Converter

Wind Turbine — Static Power Converter

Photovoltaic Cells — Static Power Converter

VEHICLE MOBILE GENERATORS

MOBILE MICROGRID SYSTEM

EPCC Modules

Loads

TOC

Forward Base / Camp

Installation

Warfighter

NEXTENERGY

Economic Security through Energy Diversity

Electronic Power Control & Conditioning (EPCC) Module: Concept Design

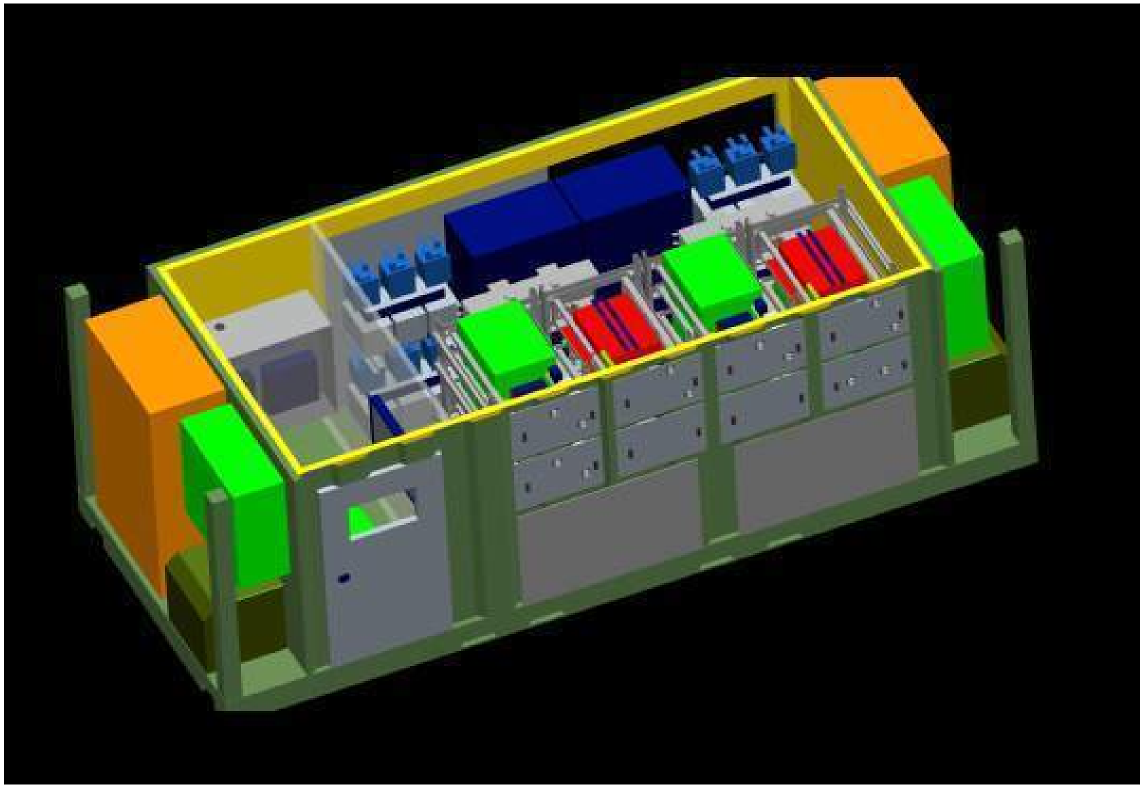
Integrated Electrical Power Control and Conditioning System

- That concurrently utilizes a wide range of AC and DC power sources that can be easily deployed to any location in the world within 48 hours (supporting deployed military operations / natural disasters / terrorist actions)

Capability

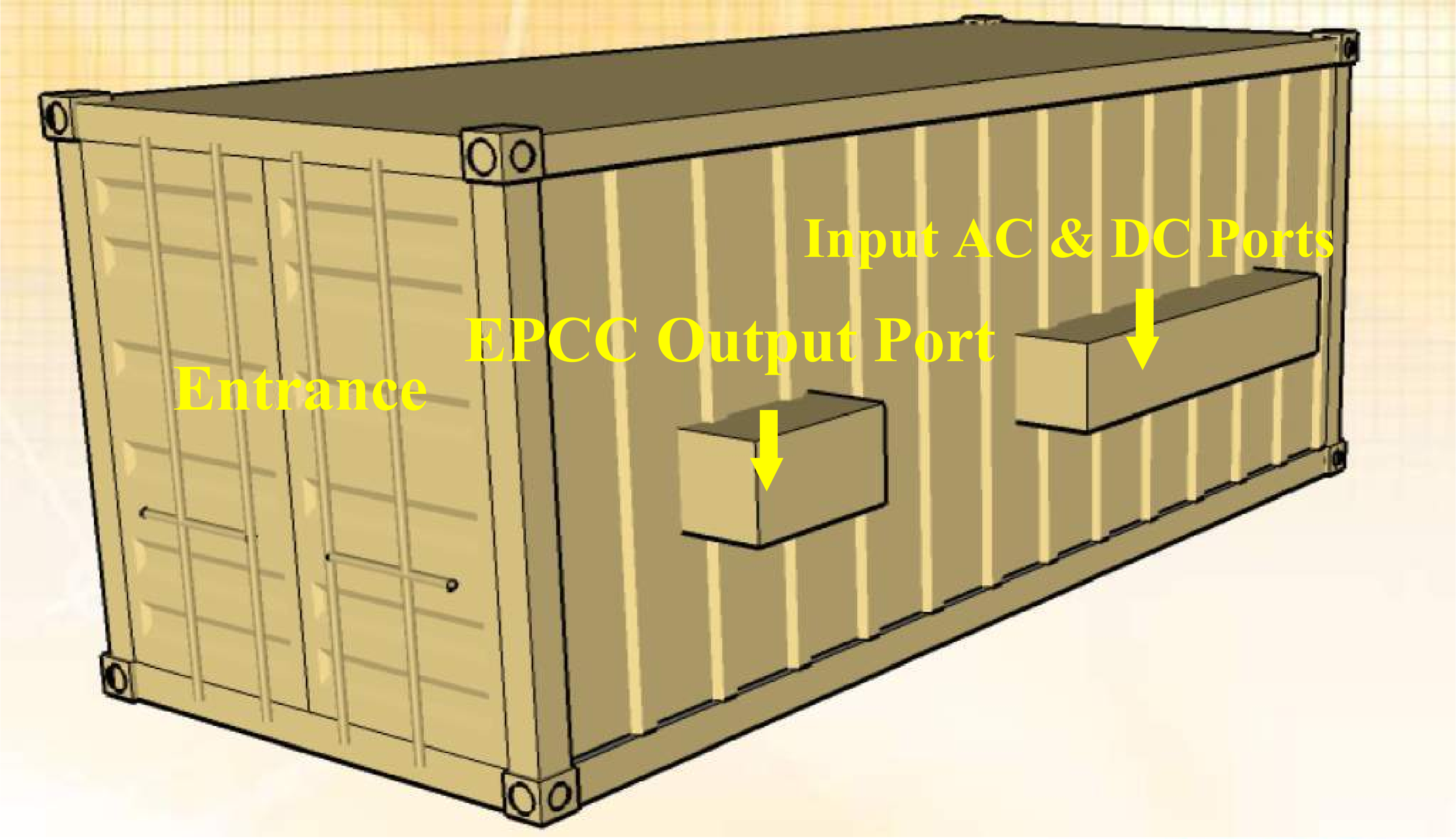
- Produce the *electrical power quality needed* to operate all loads including critical electronics-based military equipment
- Rapidly *manage several concurrent alternative power sources*
- Demonstrate *reduced vulnerability to attack* (i.e. minimize single point of failure scenarios)
- Utilize existing distributed generation strategies, vehicles with *exportable power,* and *renewable* technologies to reduce JP-8 use.

EPCC Module: Initial Concept Design

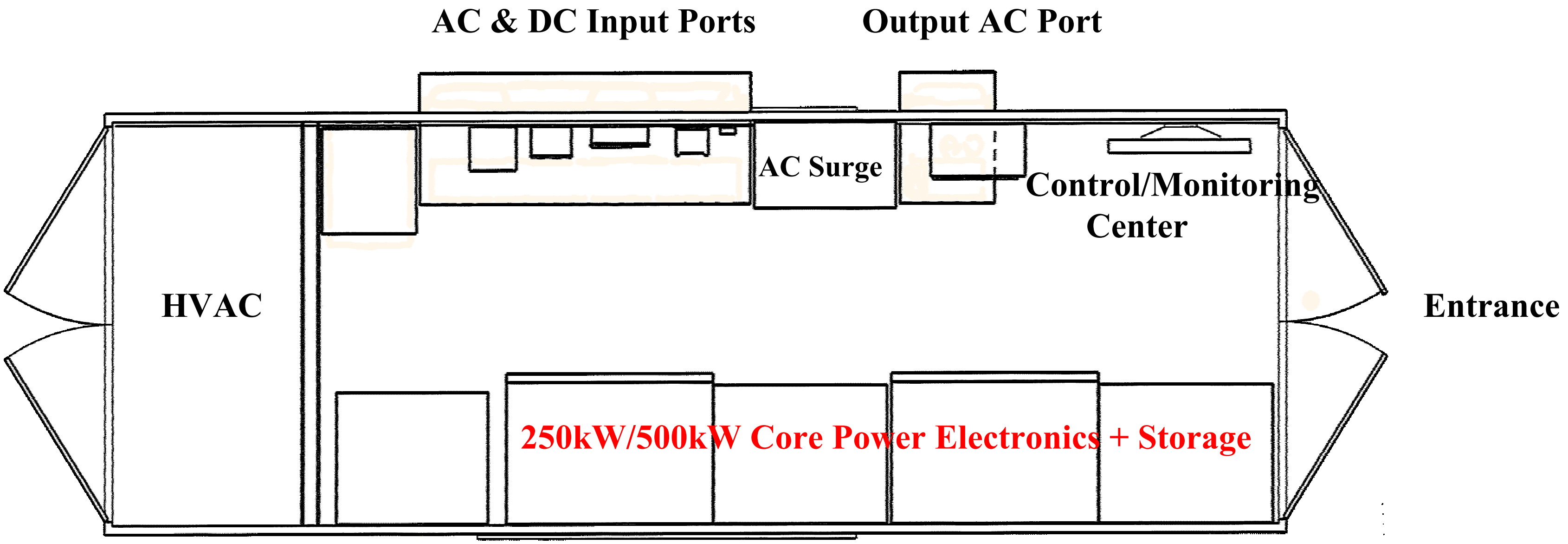


20 ft. ISO Container – Modular Design for easy Maintenance

EPCC Container: Present 8’ x 8’ x 24’ ---- Future 8’ x 8’ x 20’



EPCC Container: Present 8’ x 8’ x 24’ ---- Future 8’ x 8’ x 20’



EPCC Module: Alpha System

NEXTENERGY

Economic Security through Energy Diversity

EPCC Module

Input Port Types

- AC port c/w multi-tap transformer allowing standard voltages from 208Vac to 600Vac (likely to be engineered out).
- AC port at 480Vac directly coupled to the Power Control & Conditioning (PCC) module.
- AC/DC port at 56V to 545V limited to 60kW and 300A.
- DC port at 24Vdc to 80Vdc limited to 24kW and 300A.

Critical Components

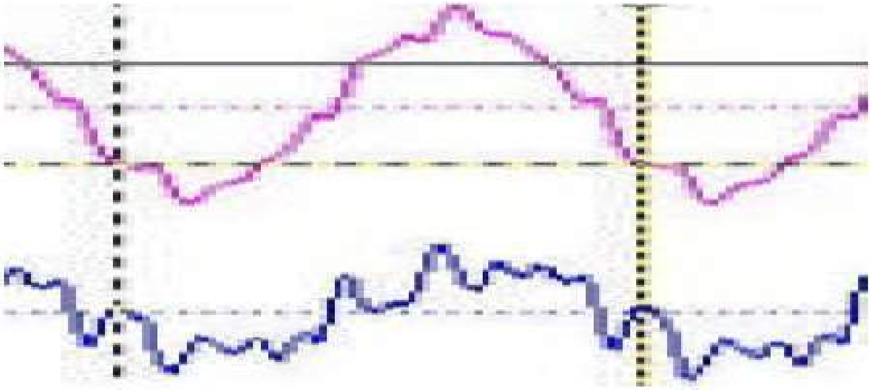
- DC/DC converter system delivering 480V to the PCC module.
- Ultra capacitor delivering at least 95kW for up to 5 sec (generator transient mgt.)
- Dual 275kVA/250kW PCC modules.

180kW DG w/o & w/ EPCC Unit: Output Voltage w/Loads*

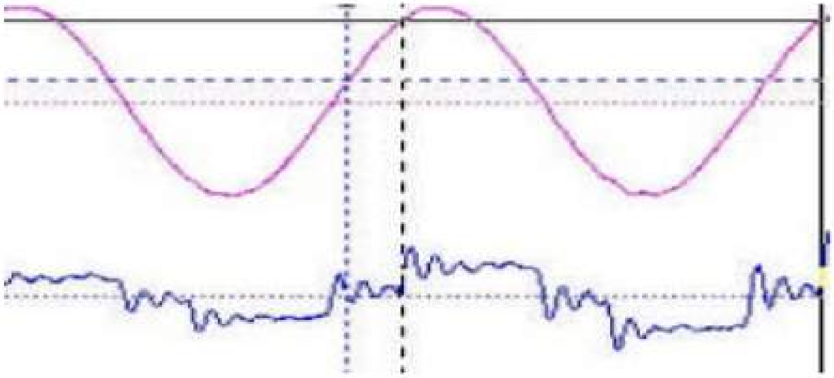
** Top Photos ------ w/30kVA UPS Transformer @ No Load “Continuous Operation”*

** Bottow Photos ------ w/50HP Motor Across-the-Line Start*

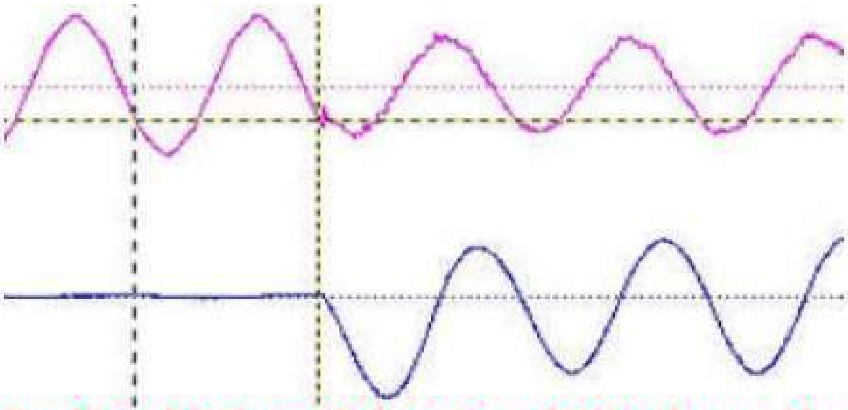
180kW DG w/o EPCC Unit --------------- 180kW DG w/ EPCC Unit



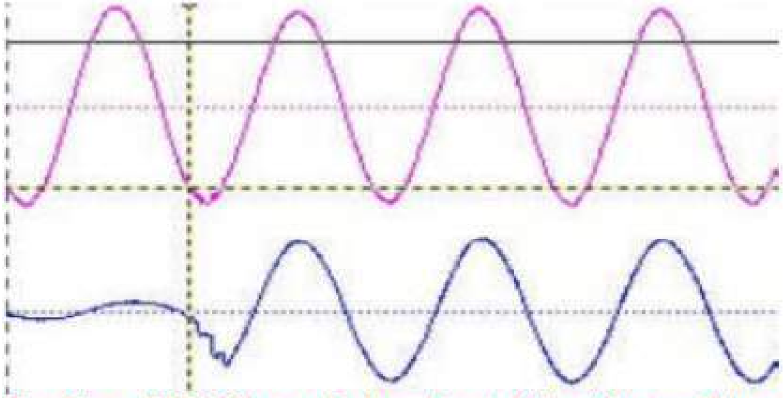
Top View: Distorted DG Output Voltage w/o EPCC Unit
Bottom View: DG Response to Non-Linear Load Current



Top View: Non-Distorted EPCC Output Voltage Waveform
Bottom View: Identical Non-Linear Load Current at EPCC



Top View: DG Output Voltage Sag (~35%) w/ System Motor Load Surge Current w/o EPCC Unit
Bottom View: ~50HP Motor Inrush Surge Current on DG



Top View: EPCC Output Voltage Sag (~5%) w/ System Motor Load Surge Current
Bottom View: ~50HP Motor Inrush Surge Current on EPCC Output

EPCC Module

Project Schedule

- Refine the baseline design, fabricate, deliver and test the Alpha prototype – to be completed by *March 2008*.
- Refine the Alpha design, fabricate, deliver, deploy and test the Beta prototype – to be completed by *December 2008*.
- Administered as a TARDEC / NAC line item.
- Refine the Beta design to comply with MIL STD 810 and fabricate 1 Gamma prototype – to be completed by *June 2009.*
- Administered as a DLA line item.

Life Cycle Cost Analysis (LCCA)

- Requested by OSD – Science & Technology.
- Will form the basis of the Concept of Operations (CONOPS) Report.

EPCC Module

MIL STD 810

- Environmental Test Methods for Aerospace and Ground Equipment (original USAF June 14, 1962).
- Design criteria MIL STD 810F Notice 3 (May 5, 2003).

Key Specifications

- Operational High Ambient Temperature: 49C (120F).
- High Induced (Transport & Storage)Temperature: 71C (160F)
- Operational Low Ambient Temperature: -54C (-65F).
- Low Induced (Transport & Storage) Temperature: -62F (-80F).
- Thermal Shock: Hi/Lo Ambient Conditions within 5 min.
- 18 test parameters in all including Humidity, Altitude, Fungus, Salt Fog, Sand & Dust, Acceleration (drop test) and Vibration.

NEXTENERGY

Economic Security through Energy Diversity

EPCC Module

Preliminary Achievable Targets

- Better than U.S. grid power quality with overall efficiency >90%.
- Reduce USACE Prime Power or USAF BEAR Base JP-8 consumption by 20% (fuel savings AND increased force protection – less resupply).
- Estimated low 7 figure $ savings per Brigade or Wing level deployment per year including reduced number of deployment sorties.
- Scalable from 250 kW to 500 kW to 750 kW to 1 MW (50 kW to 1 MW range likely)
- 750 kW unit will still fit in a 20ft ISO container and weigh less than 20,000 lbs (2 will fit on 1 C130).
- $700/kW for an 800 kW unit ($560K) given a production run of 10 units (about the same cost of a new 800 kW BPU at $500K).
- EPCC MicroGrid Controller (MGC) will optimize complete base electrical consumption.

* Numbers are based current level of Tactical Readiness Level (est. TRL 4) so MIL STD upgrades will vary cost.

NEXTENERGY
Economic Security through Energy Diversity

EPCC Module

Potential Markets

- U.S. Military (CONUS, OCONUS and FOB)
- U.S. Military Coalition Forces
- Homeland Security (natural disaster & terrorist action relief)
- Developing countries – regional electrification
- Developed countries – microgrid / utility grid interface.

High Power Converters for Efficient Transmission Solutions

Dr. Le Tang

VP & Head of Corporate Research Center

ABB Inc.

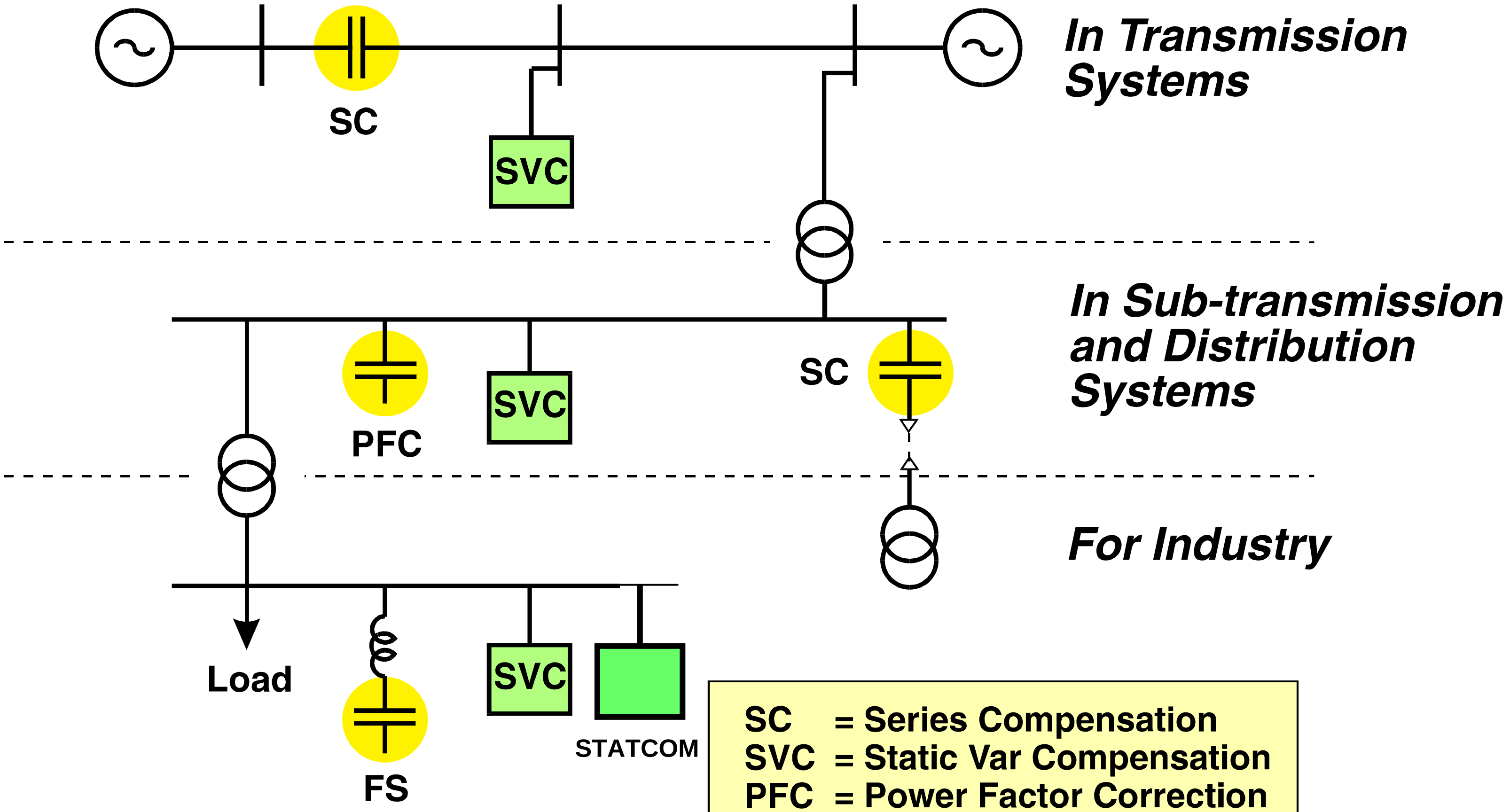
High Megawatt Power Converter Technology R&D Roadmap Workshop

April 8, 2008

FACTS Topics

- FACTS Technologies
  - Static Var Compensators - SVC
  - Series Capacitors - SC
  - Thyristor Controlled Series Capacitors - TCSC
  - Static Synchronous Compensator - STATCOM
- Selected FACTS Projects
  - STATCOM with Energy Storage

Basic FACTS Devices



SC = Series Compensation
SVC = Static Var Compensation
PFC = Power Factor Correction
FS = Filter Systems

FACTS Portfolio – Two main areas

Shunt Compensation

- SVC
- **STATCOM (SVC Light)**

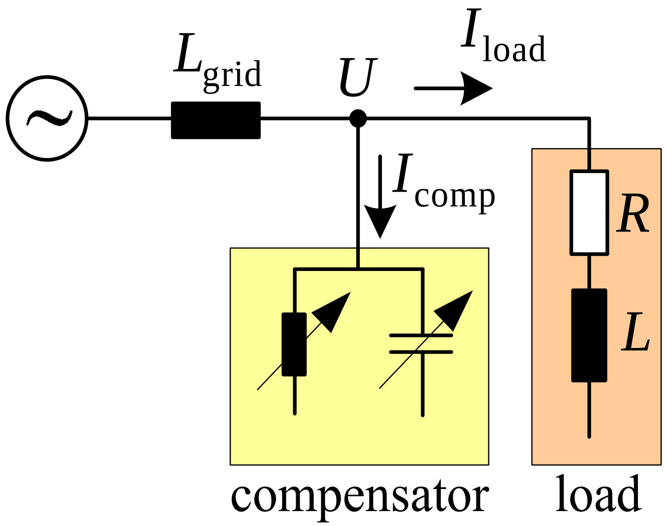
Series Compensation

- Fixed
- Controllable

Basic Controller Function

Classic SVC

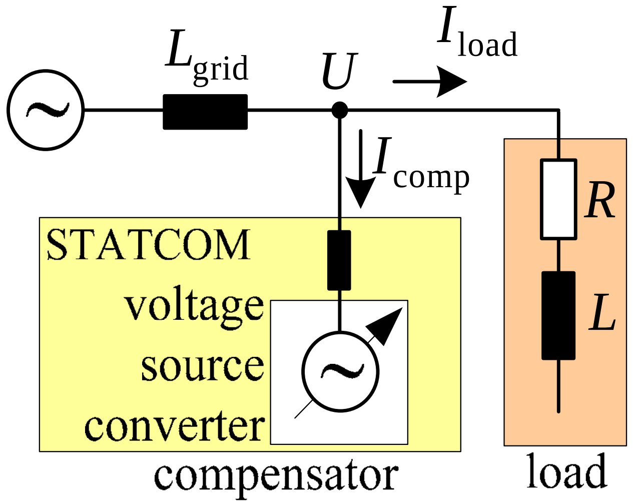
- Variable inductors and capacitors obtained by thyristors



- $Q \sim U^2$
- Load balancing

STATCOM (Static Compensator)

- VSC (Voltage Source Converter) controls current through inductor



- Q~U
- High bandwidth => quicker control
- Active filtering
- Load balancing
- Flicker mitigation
- Low content of harmonics

History of ABB’s SVC Light

- Manufactured 10 SVC Light

SVC Light Pilot

Hällsjön	*1997*	*3 MW*	*(pilot HVDC Light)*
Hagfors	1999	±22 MVAr	(Flicker mitigation for EAF)
Mosel	2000	±38 MVAr	(Flicker mitigation for EAF)
Eagle Pass	2000	±36 MW	(B2B with SVC priority)
Evron	2003	±16 MVAr	(Traction power supply conditioner, load balancing, harmonic filtering)
Polarit	2003	164 MVAr	(Flicker mitigation for EAF)
Holly	2004	±95 MVAr	(Utility, voltage regulation)
ZPSS	2006	164 MVAr	(Flicker mitigation for EAF)
Ameristeel	2006	64 MVAr	(Flicker mitigation for EAF)
Mesney	2007	±13 MVAr	(Traction power, load balancing, filtering)

steelworks **utility** **EAF = electric arc furnace**

FACTS with Energy Storage

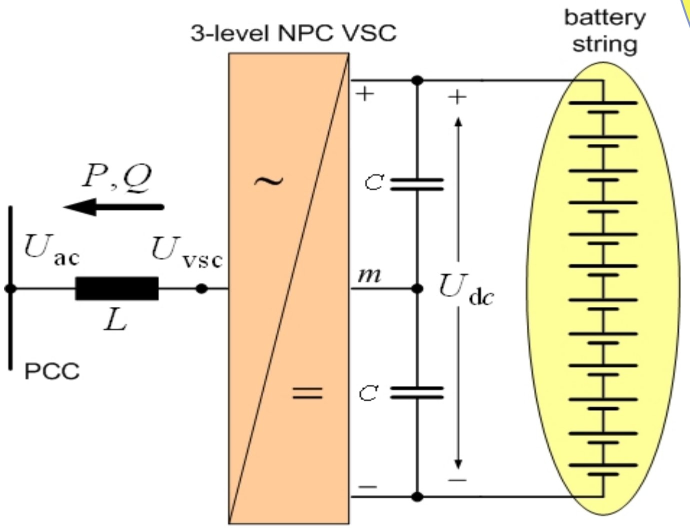
SVC Light

flicker compensation
harmonic filtering
power-factor correction
voltage regulation
load balancing

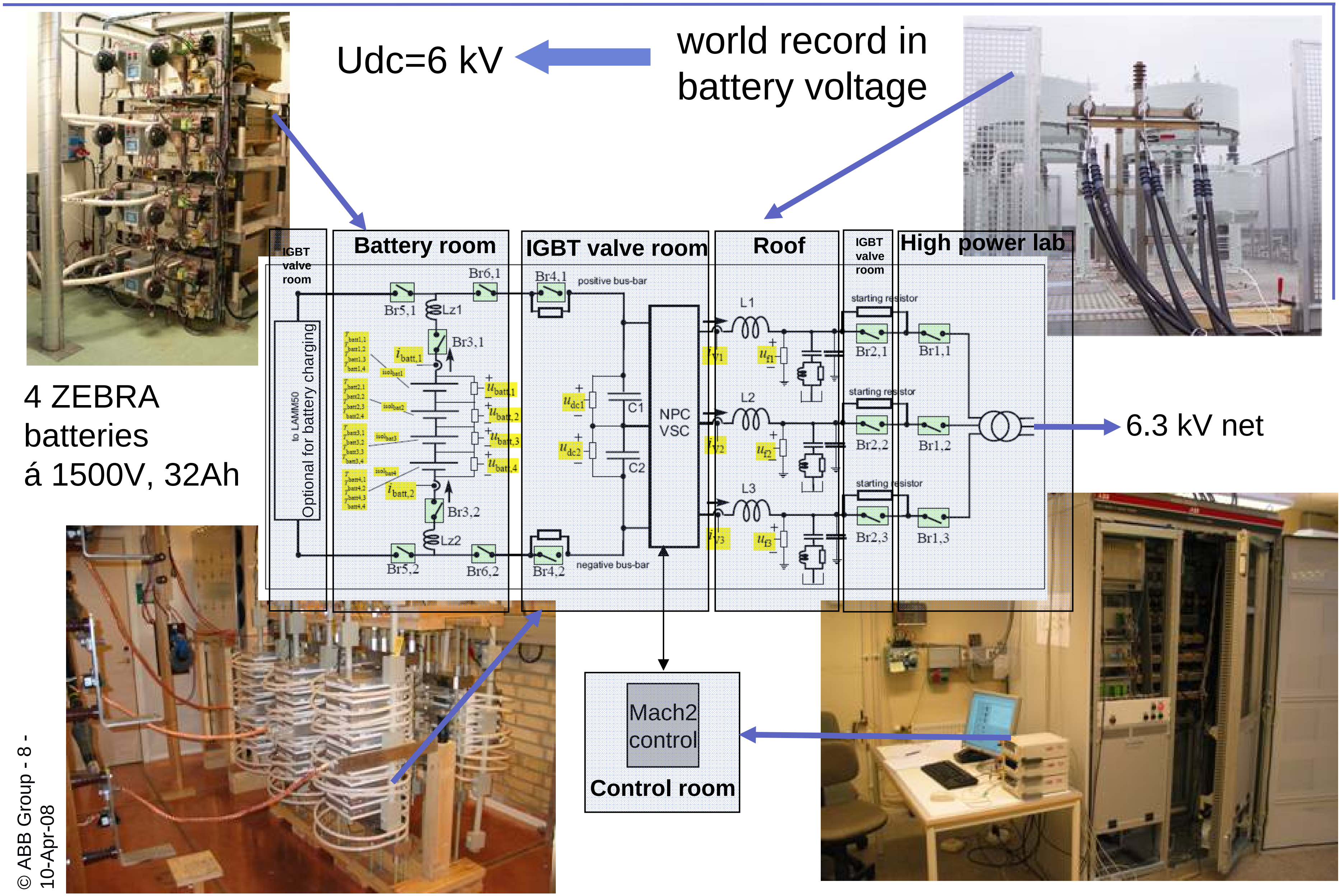
Increased functionality

SVC Light
+
energy storage

load leveling (energy)
flicker compensation
harmonic filtering
power-factor correction
voltage regulation
load balancing
DIP mitigation



Laboratory Demonstration 2005/2007



Udc=6 kV

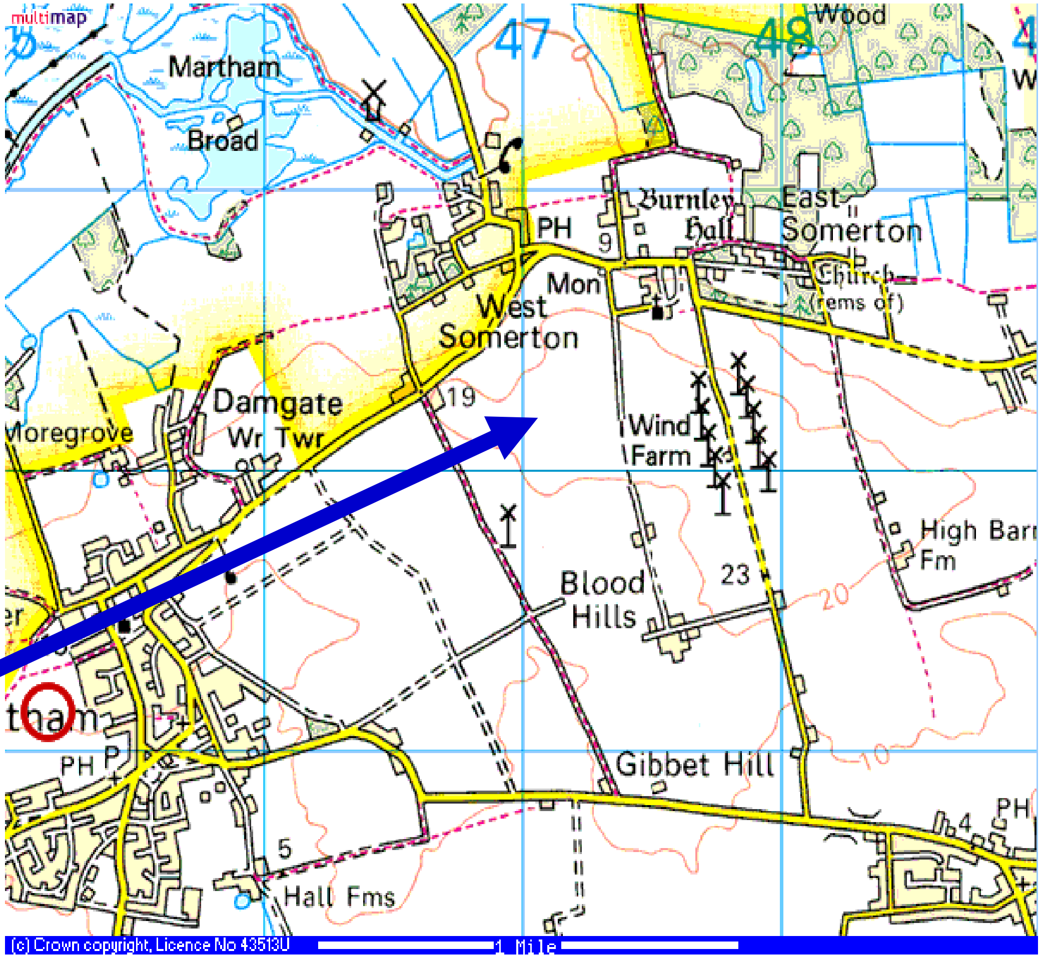
world record in battery voltage

4 ZEBRA batteries
á 1500V, 32Ah

6.3 kV net

SVC Light Energy Storage R&D Project

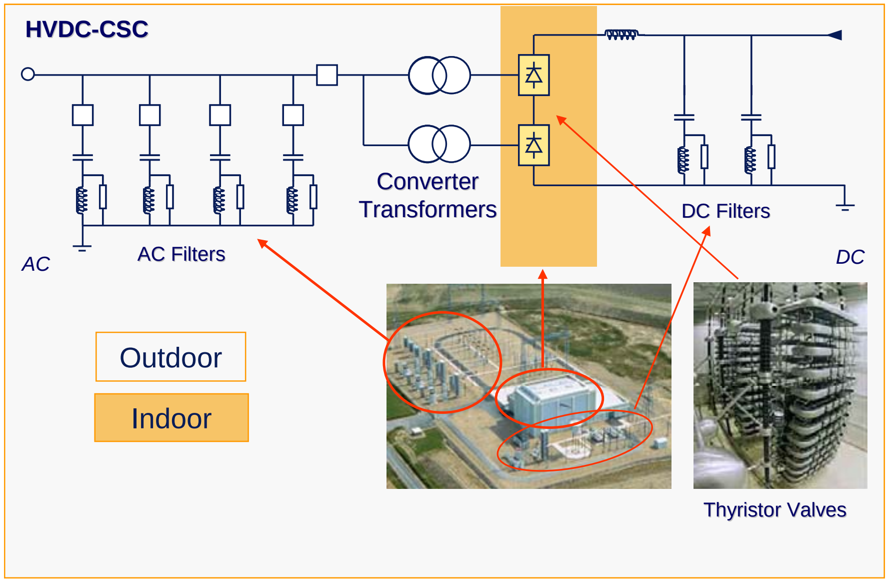
- The SVC Light Energy Storage will be located in UK.
- In close vicinity to the SVC Light Energy Storage two Wind Farms are connected to the 11 kV distribution system.

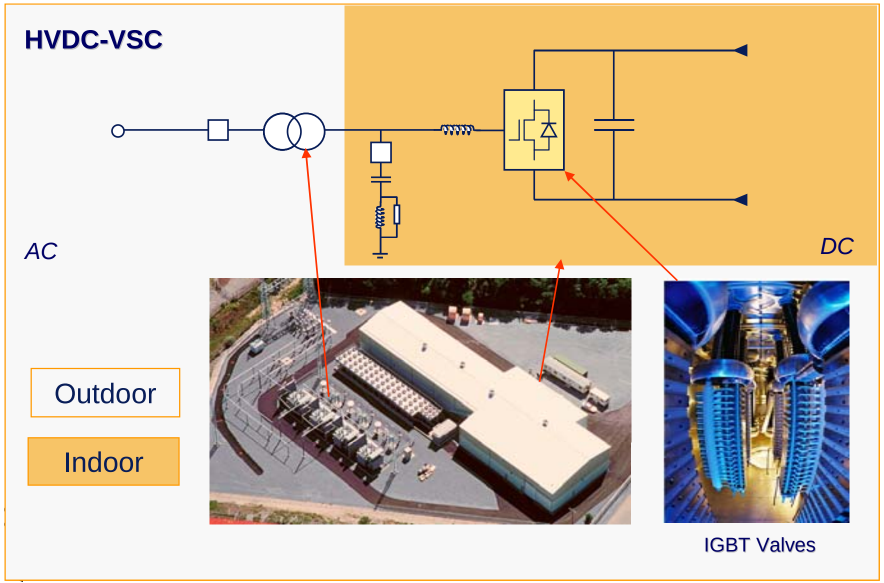


HVDC Topics

- HVDC Technologies
  - Converter Stations
  - Cables
- Selected HVDC Projects
  - Estonia – Finland (Estlink) black start field tests
  - Norway – Netherlands (Norned)
  - Outaouais
  - E.ON, Borkum 2 - 400 MW Offshore Wind
  - Caprivi Link
  - Xiangjiaba – Shanghai, ± 800 kV, 6400 MW
- Vision
  - What’s New

Core HVDC Technologies





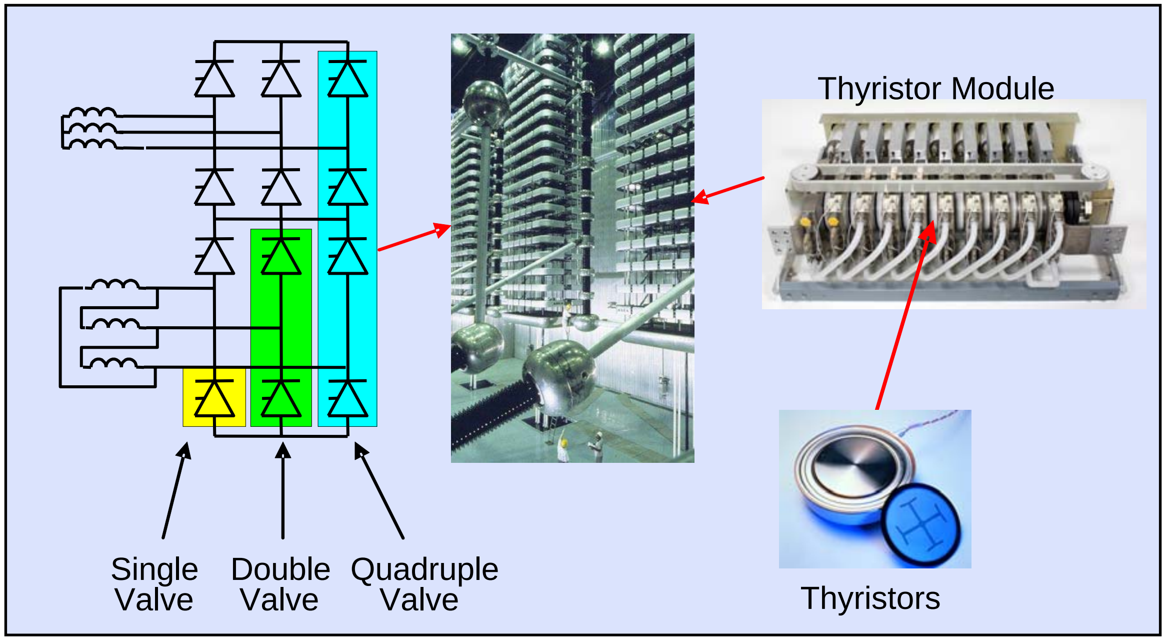
HVDC Classic

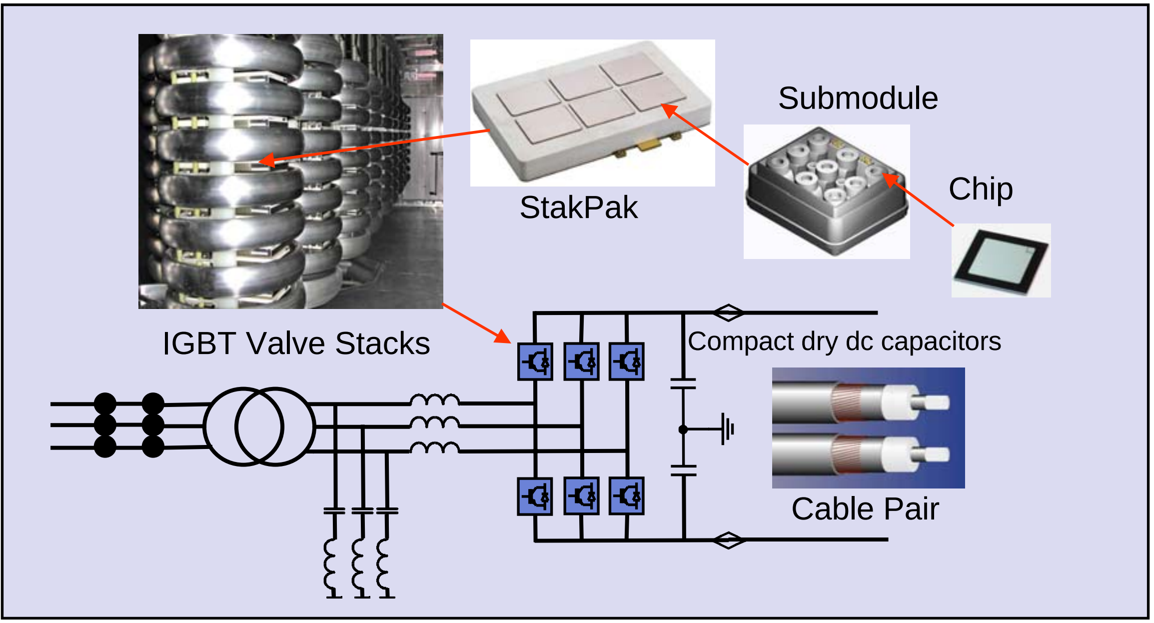
- Current source converters
- Line-commutated thyristor valves
- Requires 50% reactive compensation (35% HF)
- Converter transformers
- Minimum short circuit capacity > 2x converter rating, > 1.3x with capacitor commutation

HVDC Light

- Voltage source converters
- Self-commutated IGBT valves
- Requires no reactive power compensation (~15% HF)
- Standard transformers
- Weak system, black start
- U/G or OVHD
- Radial wind outlet regardless of type of wind T-G

HVDC Converter Arrangements





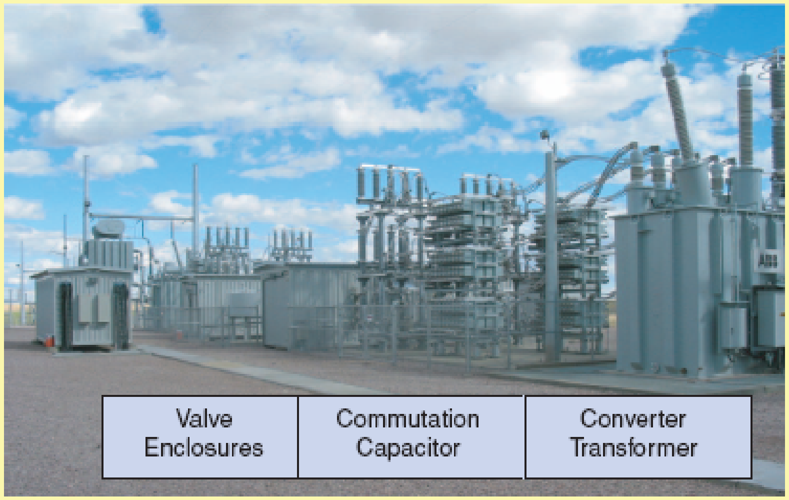
HVDC Classic

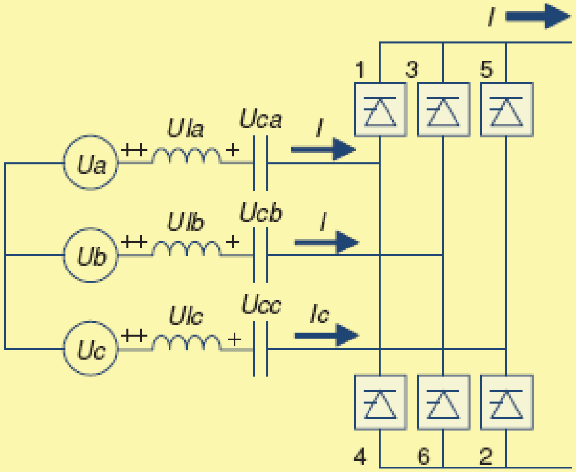
- Thyristor valves
- Thyristor modules
- Thyristors
- Line commutated

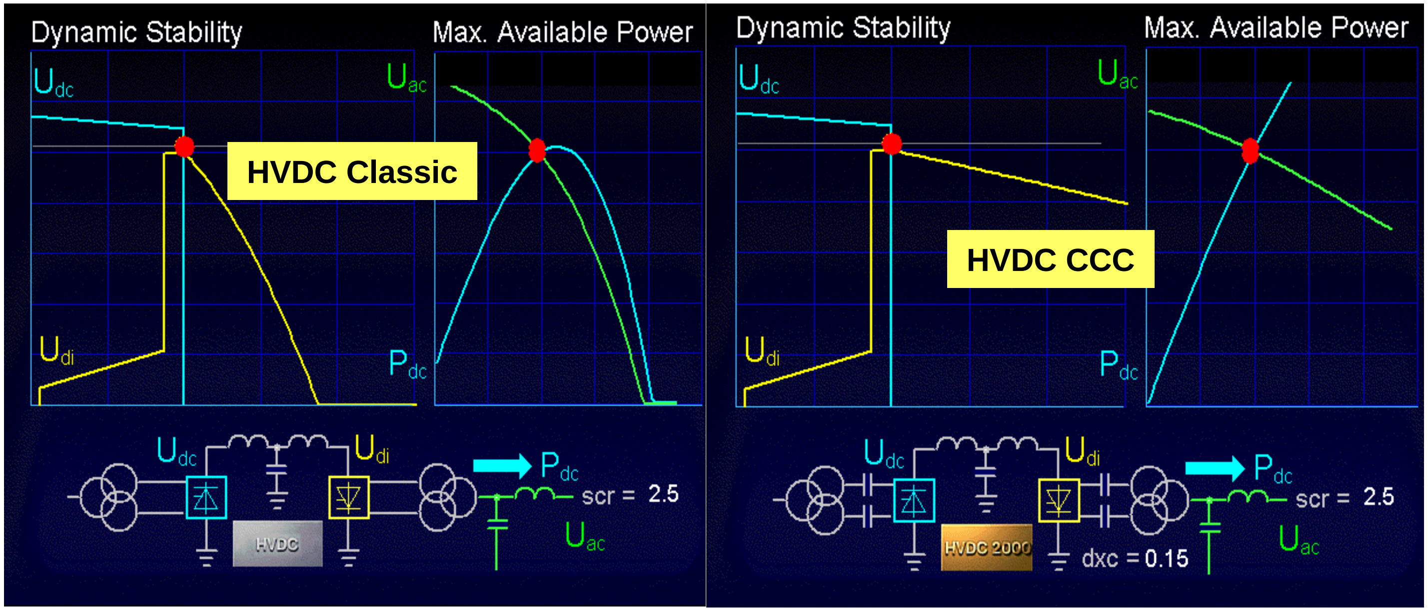
HVDC Light

- IGBT valves
- IGBT valve stacks
- StakPaks
- Submodules
- Self commutated
- Compact dry dc capacitors

Modular Back-to-Back CCC Asynchronous Tie







- Improved stability for weak systems due to commutation capacitor
- Higher power for given location
- Simplified reactive power control
- Garibi: 4x550 MW
- Rapid City Tie: 2x100 MW
- Modular design for shorter construction time
- Least expensive, most efficient asynchronous tie technology

Maturation of HVDC & SVC Light


1) 3MW, ±10kV


2) 50MW, ±80 kV


3) 7MW, ±10kV


4) 3x 60MW, ±80kV

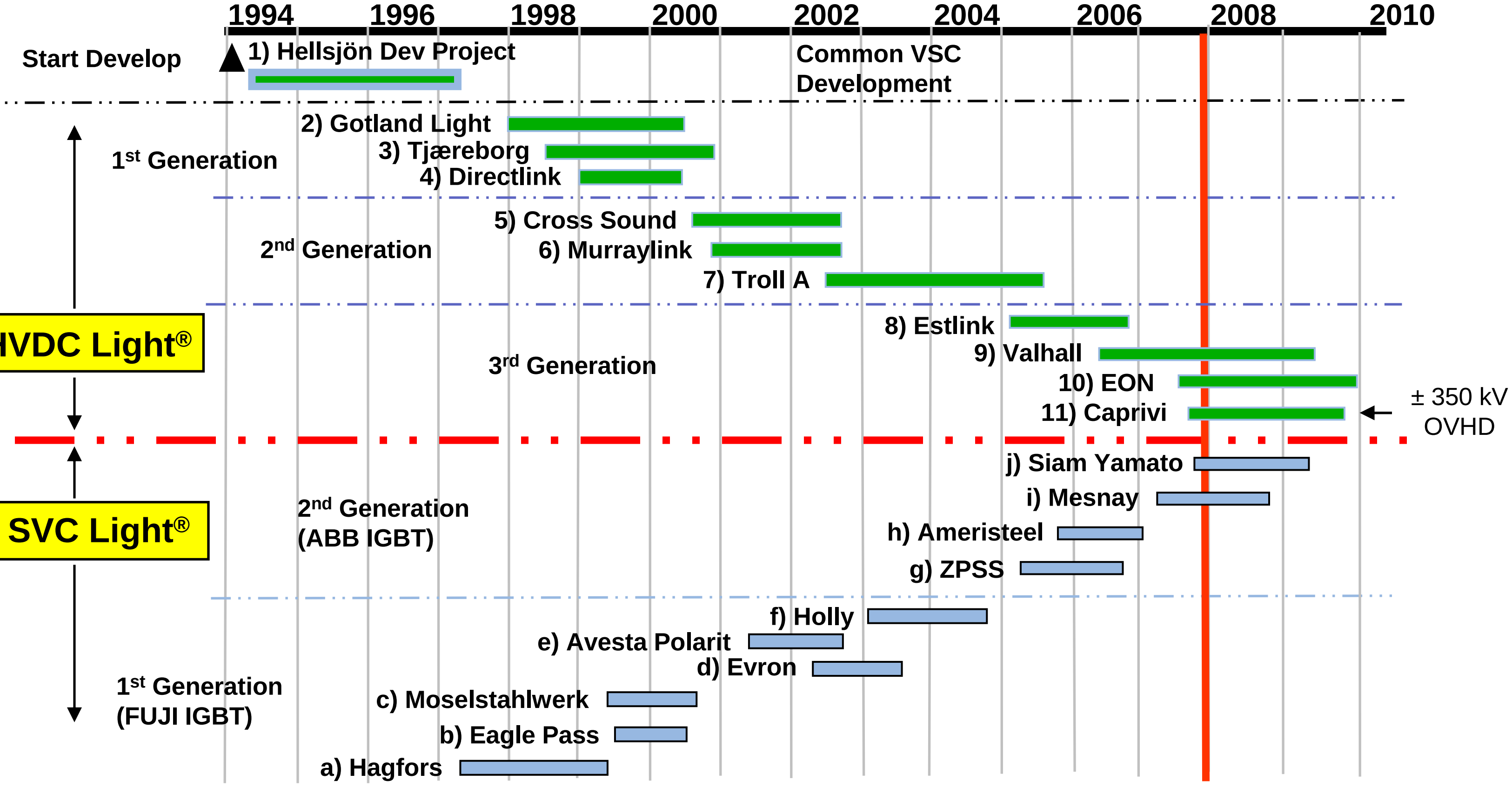

5) 330MW, ±150kV


6) 200MW, ±150kV


7) 2x40MW, ±60kV


8) 350MW, ±150kV

ABB IGBT



Start Develop

1) Hellsjön Dev Project

Common VSC Development

1st Generation

2) Gotland Light
3) Tjæreborg
4) Directlink

2nd Generation

5) Cross Sound
6) Murraylink
7) Troll A

3rd Generation

8) Estlink
9) Valhall
10) EON
11) Caprivi

± 350 kV OVHD

🟩 **HVDC Light®**

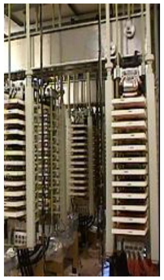
▭ **SVC Light®**

2nd Generation (ABB IGBT)

j) Siam Yamato
i) Mesnay
h) Ameristeel
g) ZPSS

f) Holly
e) Avesta Polarit
d) Evron
c) Moselstahlwerk
b) Eagle Pass
a) Hagfors

1st Generation (FUJI IGBT)




a) 0-44 MVAR

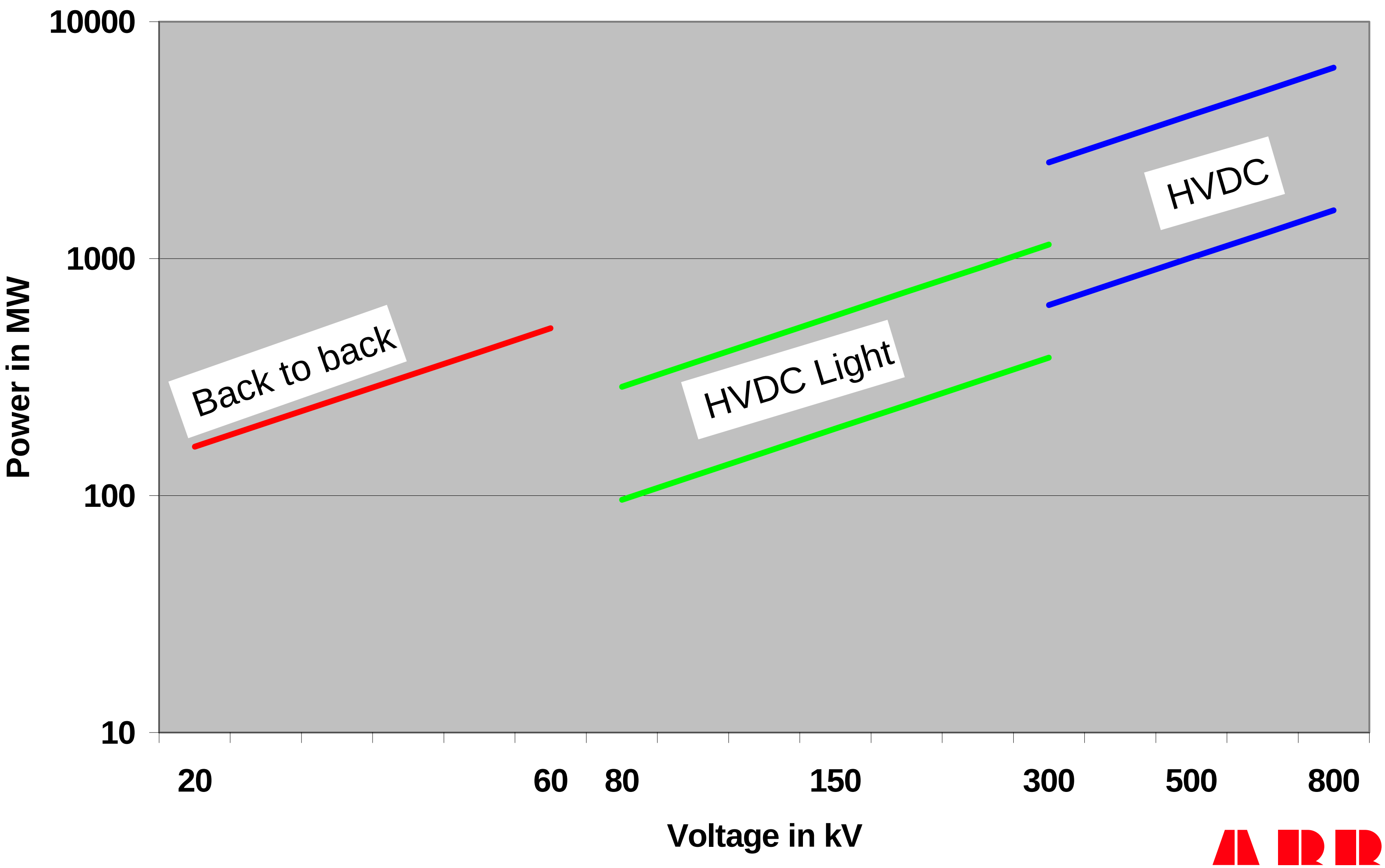

b) 2x36 MVAR


e) 0-164 MVAR


f) ±100 MVAR


g) 0-164 MVAR

Power Ranges HVDC-Classic and HVDC-Light



Mass-Impregnated Paper & Solid Dielectric XLPE Cables

HVDC Classic

- Type tested to 500 kV
- Insulation, lapped mass-impregnated oil paper
- Medium/high weight
- Tailored joints (5 days/joint handcrafted in field, impractical for long distance land cable installation)

HVDC Light

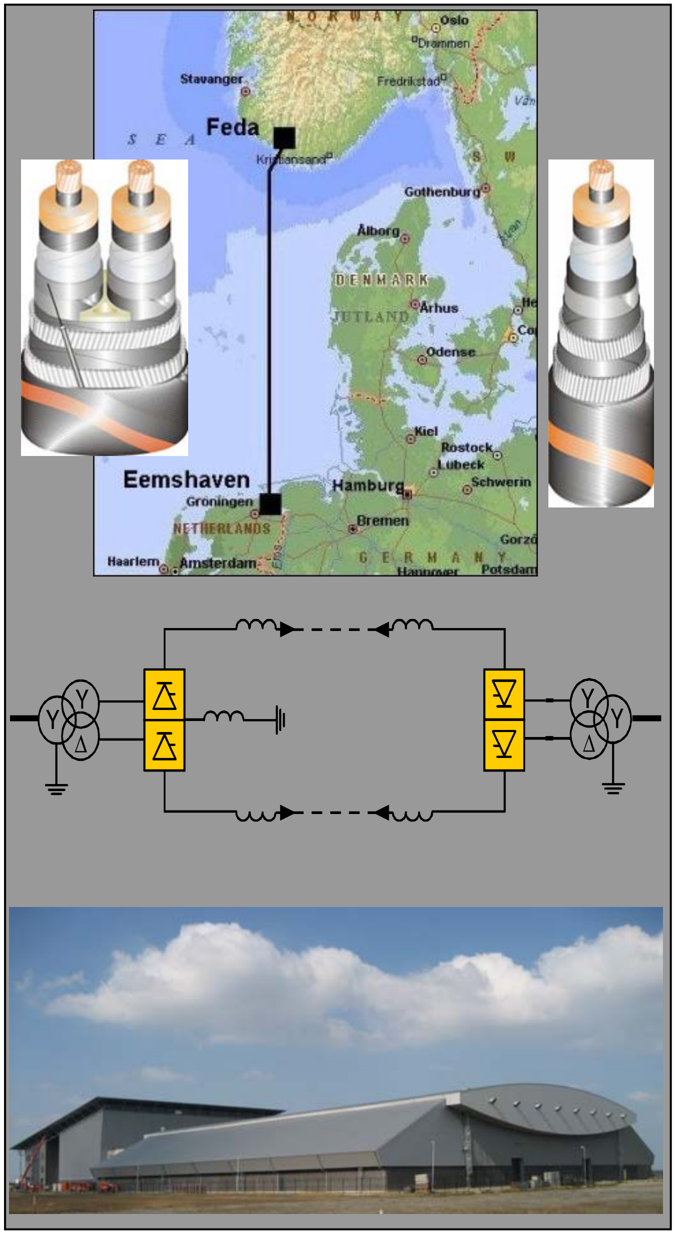
- Type tested to 320 kV
- XLPE insulation
- Low/medium weight
- Pre-molded joints (practical for long distance land cable installation)

ABB's cable factory in Sweden

Estlink – HVDC Light between Estonia & Finland

Client:	Nordic Energy Link, Estonia
Contract signed:	April 2005
In service:	November 2006
Project duration:	19 months
Capacity:	350 MW, 365 MW low ambient
AC voltage:	330 kV at Harku
	400 kV at Espoo
DC voltage:	±150 kV
DC cable length:	2 x 105 km (31 km land)
Converters:	2 level, OPWM
Special features:	Black start Estonia, no diesel
Rationale:	Electricity trade
	Asynchronous Tie
	Long cable crossing
	Dynamic voltage support
	Black start

Submarine Cable: NorNed Cable HVDC Project



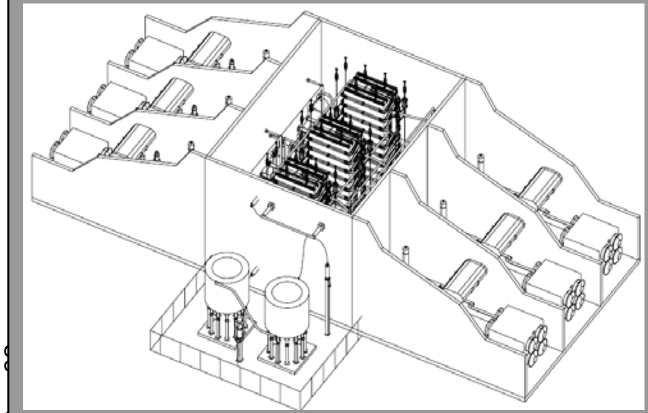
Scope

- 700 MW HVDC cable interconnection Norway - Netherlands
- ± 450 kV monopole mid-point ground (900 kV converters)
- Cable length: 2 x 580 km
- Sea depth: up to 480 meters
- 400 kV ac voltage at Eemshaven
- 300 kV ac volgage at Freda

Project Basis

- Customer: Statnett (NOR), Tennet (NLD)
- Asynchronous networks, long cable
- Power control suits markets
- Project start: January 2005
- Project duration: ~ 3 years

Outaouais Asynchronous Tie- Summary



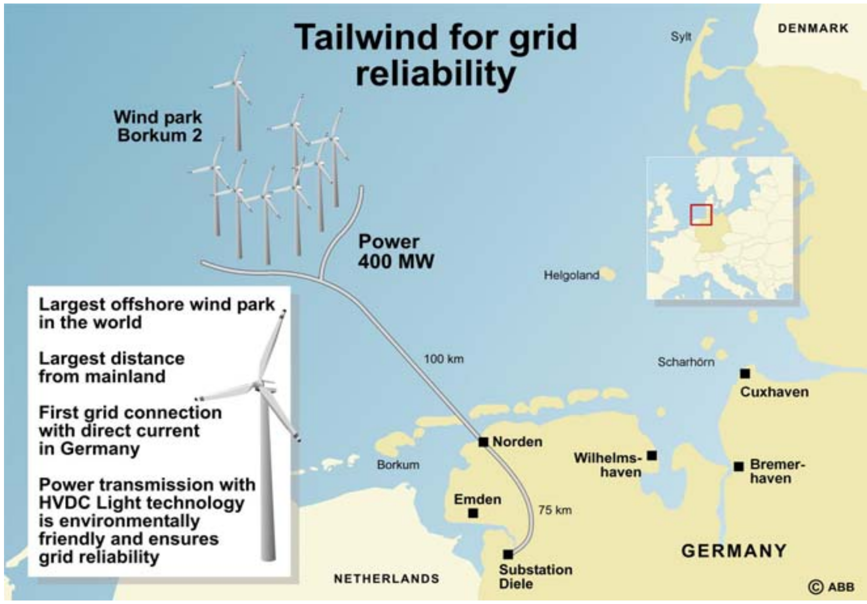
Scope

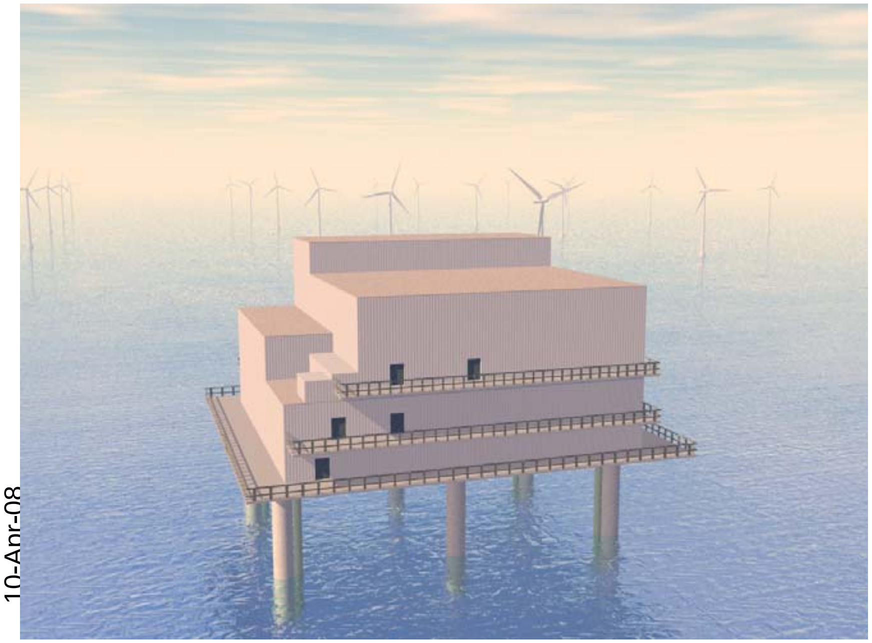
- 1250 MW HVDC B t B Interconnection Québec-Ontario
- Two independent converters of 625 MVA
- Includes 14 x 250 MVA 1-phase converter transformers

Project Basis

- Customer: Hydro-Québec (HQ)
- Project to export power from Québec to Ontario (Hydro Québec and Hydro One)
- Ontario gets access to clean hydroelectric power during peak times and decreases dependency on coal from US
- HQ sells at peak and buys at low (pump storage)
- Provides stability and reliability to both grids

Borkum 2, E.ON Netz





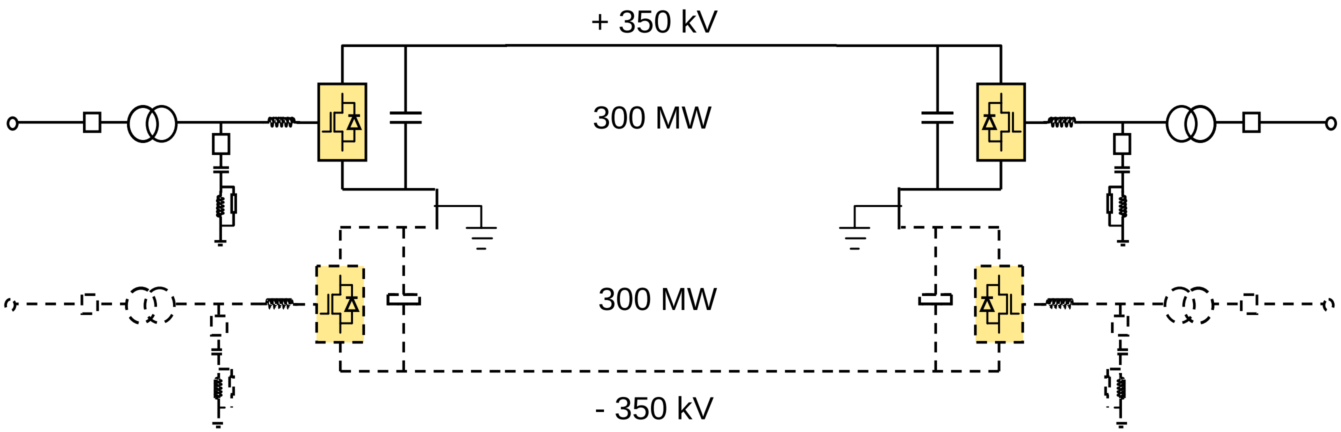
Scope

- 400 MW HVDC Light Offshore Wind, North Sea - Germany
- ±150 kV HVDC Light Cables (route = 130 km by sea + 75 km by land)
- Serves 80 x 5 MW offshore wind turbine generators
- Builds upon HVDC Light experience with wind generation at Tjaerborg and Gotland
- Controls collector system ac voltage and frequency

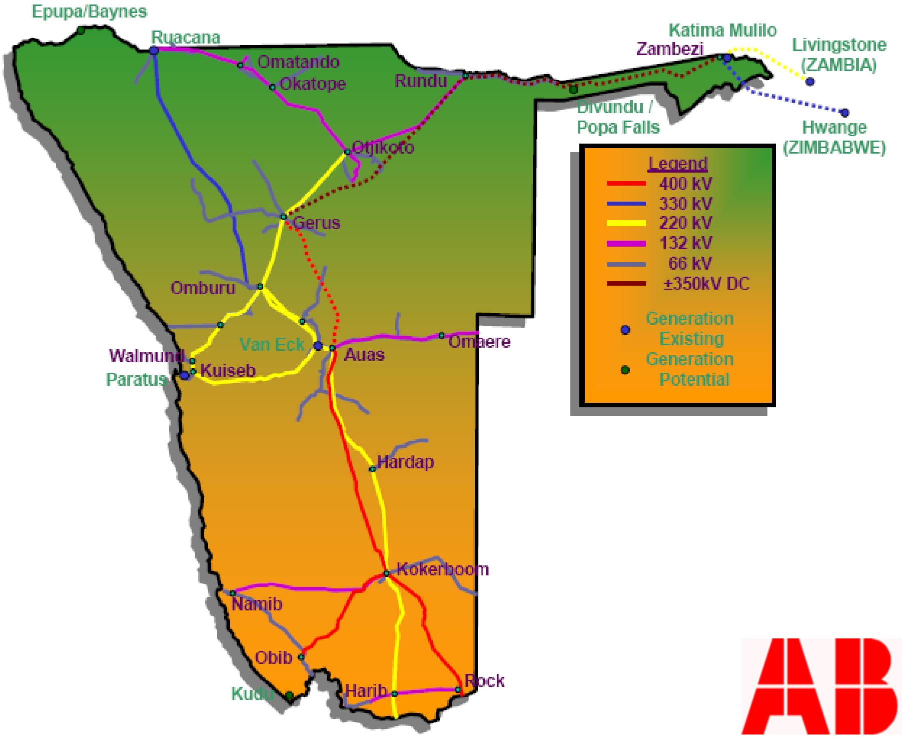
Project Basis

- Customer: E.ON Netz GmbH
- Project serves 80 x 5 MW offshore wind turbine generators
- Germany gets access to clean wind power with higher capacity factor than land based wind generation
- Provides stability and reliability to receiving system
- 24 month delivery time
- Saves 1.5 M tons CO2/year

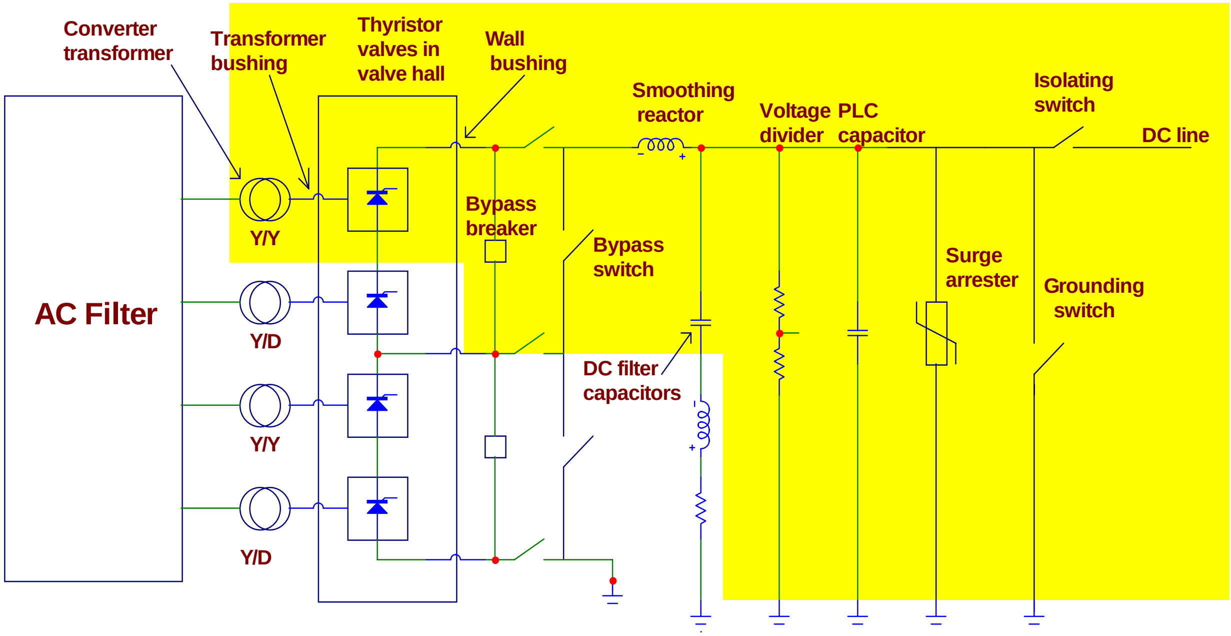
Caprivi Link, NamPower



- 300 MW, 350 kV HVDC Light Monopole with ground electrodes
- Expandable to 600 MW, ± 350 kV Bipole
- ± 350 kV HVDC Overhead Line
- Links Caprivi region of NE Namibia with power network of central Namibia and interconnects with Zambia, Zimbabwe, DR Congo, Mozambique
- Improves voltage stability and reliability
- Length of 970 km DC and 280 km (400kV) AC



800 kV HVDC Transmission

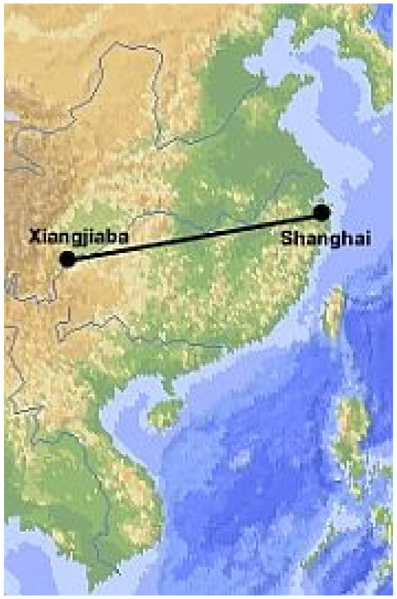


🟨 Pole equipment exposed to 800 kV dc

Long term test circut for 800 kV HVDC

± 800 kV, 6400 MW (4 x 1600) HVDC Link

Xiangjiaba - Shanghai ± 800 kV UHVDC Project



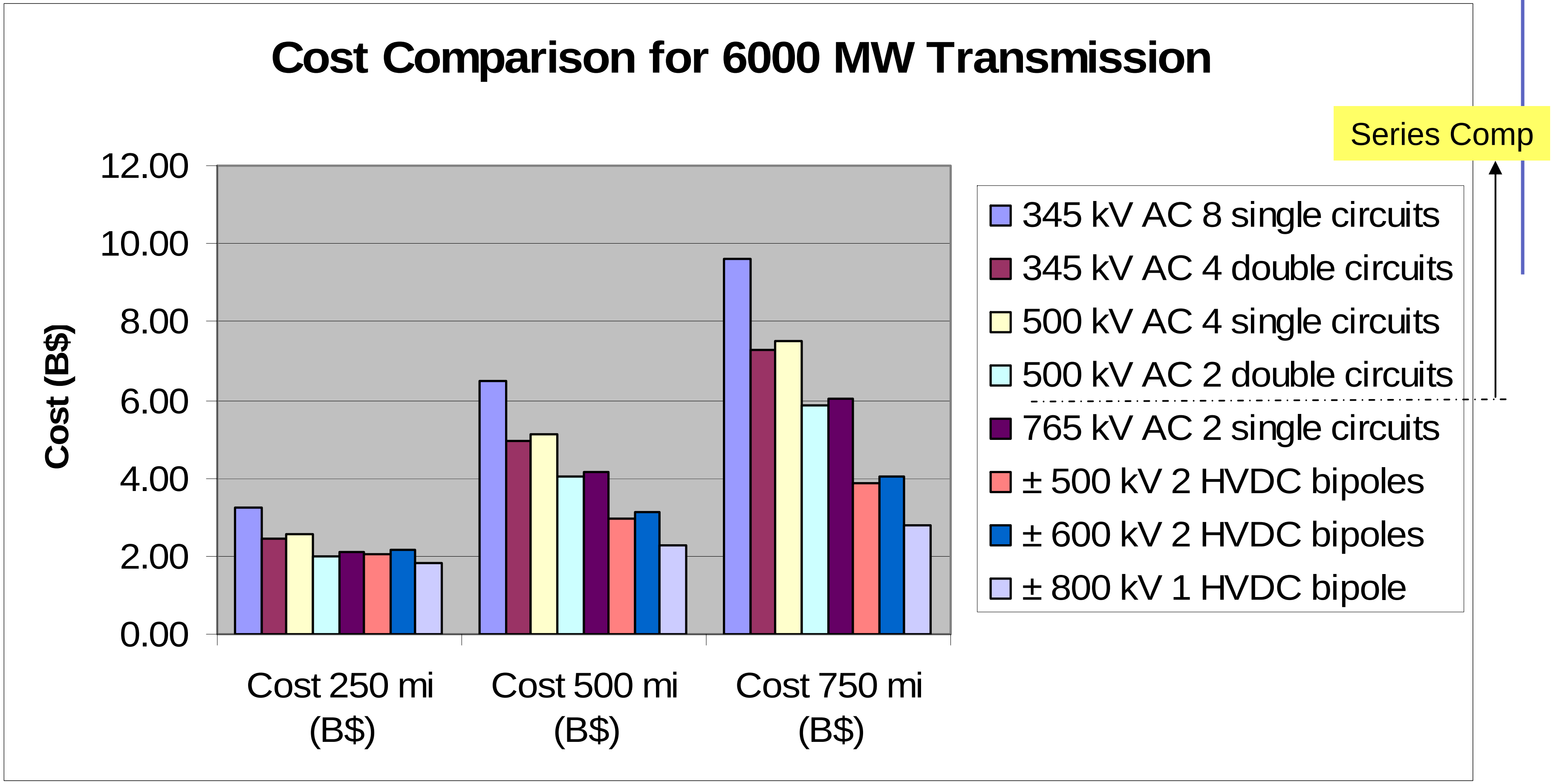
Scope

- Power: 6400 MW (4 x 1600 MW converters)
- ± 800 kV DC transmission voltage
- System and design engineering
- Supply and installation of two ± 800 kV converter stations including 800 kV HVDC power transformers and switchgear
- Valves use 6 inch thyristors and advanced control equipment

Project Basis

- Customer: State Grid Corporation of China
- Project delivers 6400 MW of Hydro Power from Xiangjiaba Power Plant in SW China
- Length: 2071 km (1286 mi), surpasses 1700 km Inga-Shaba as world’s longest
- Pole 1 commissioned in 2010, pole 2 in 2011
- AC voltage: 525 kV at both ends

Cost of 6000 MW Transmission Alternatives



Note: Transmission line and substation costs based on Frontier Line transmission subcommittee and NTAC unit cost data.

Summary of Power Conversion Requirements

- High rating semiconductor devices
- High reliability
- Modularity
  - Flexible for reconfiguration and expansion
  - Spare parts
- Small footprint
- Transformer less connection
- Controllability, dynamic response (4Q operation), and black start
- Less filtering requirement
- Low losses
- Self-diagnostic/Self-healing
- Cost

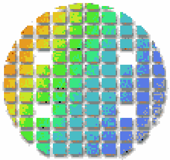
ABB

Power and productivity
for a better world™

High-Voltage, High-Frequency Devices for Solid State Power Substation and Grid Power Converters

Allen R. Hefner
Semiconductor Electronics Division
National Institute of Standards and Technology
Gaithersburg, MD 20899
hefner@nist.gov

The devices discussed in this paper were produced by Cree/Powerex. NIST does not necessarily recommend or endorse the devices as the best available for the purpose.



Outline

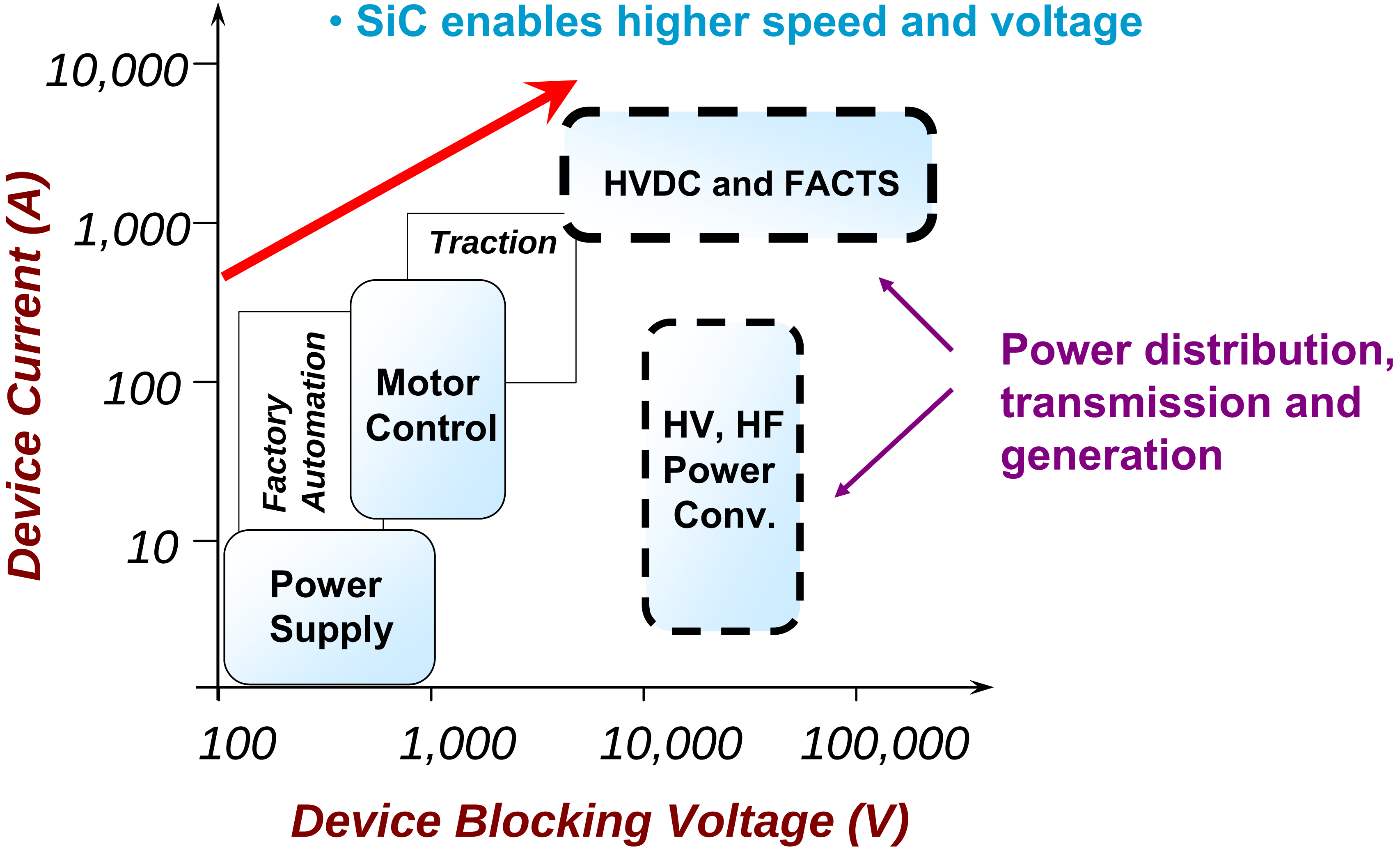
- **HV-HF SiC Power Devices**
- **DARPA HPE Program Overview**
  - **Goal: Solid State Power Substation (SSPS)**
  - **Status: 10 kV, 100 A, 20 kHz power modules**
- **Component Modeling and Circuit Simulation**
- **Impact on Grid-Connected Power Converters**

HV-HF Power Conversion

- Switch-mode power conversion and conditioning:
  - advantages: efficiency, control, functionality, size and weight
  - semiconductors from: 100 V, ~MHz to 6 kV, ~100 Hz
- New semiconductor devices extend application range:
  - 1990's: Silicon IGBTs
    - higher power levels for motor control and traction
  - Emerging: SiC Schottky diodes and MOSFETs
    - higher speed for power supplies and motor control
  - Future: HV-HF SiC MOSFET, PiN diode, Schottky, and IGBT
    - enable 15-kV, 20-kHz switch-mode power conversion

Switch-Mode Power Applications

- Switching speed decreases with voltage
- SiC enables higher speed and voltage



Power distribution, transmission and generation

SiC Power Devices

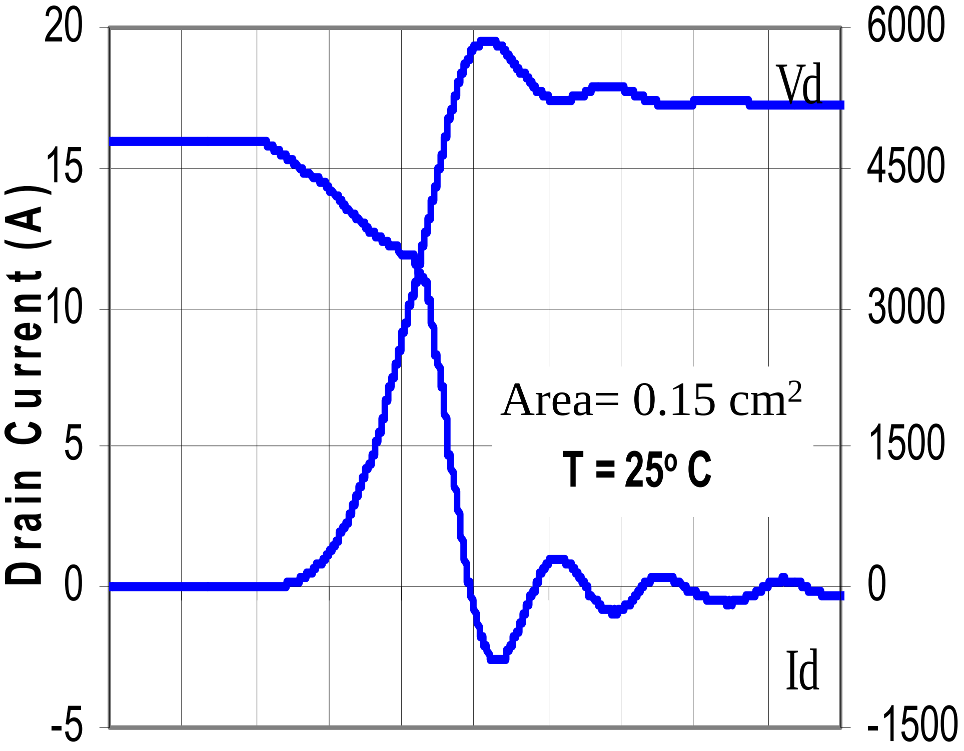
SiC wide bandgap material enables better electrical and thermal performance than Si power devices

Semi-Conductor Material	Energy Bandgap (eV)	Breakdown Electric Field (V/cm)	Thermal Conductivity (W/m·K)	Saturated Electron Drift Velocity (cm/sec)
4H-SiC	3.26	$2.2 \cdot 10^6$	380	$2.0 \cdot 10^7$
Si	1.12	$2.5 \cdot 10^5$	150	$1.0 \cdot 10^7$

- **Handles higher temperature:** larger bandgap
- **Higher voltage, current and speed:** larger breakdown field
- **Fault tolerance, Pulsed:** intrinsic-temperature, saturation-velocity and thermal-conductivity

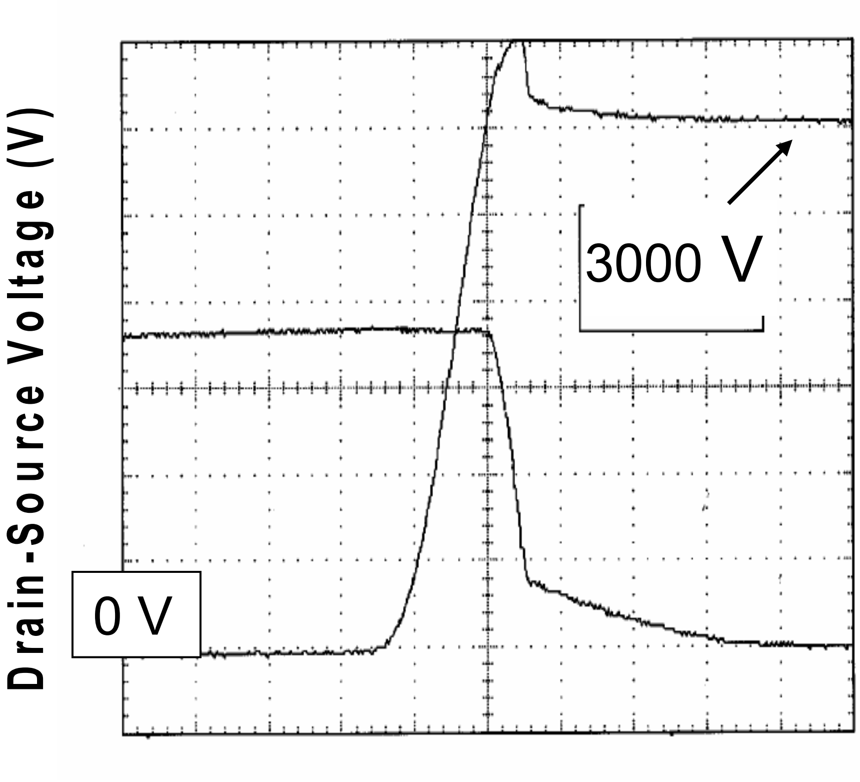
DARPA HPE MOSFET:
High Speed at High Voltage

SiC MOSFET: 10 kV, 30 ns



15 ns /div

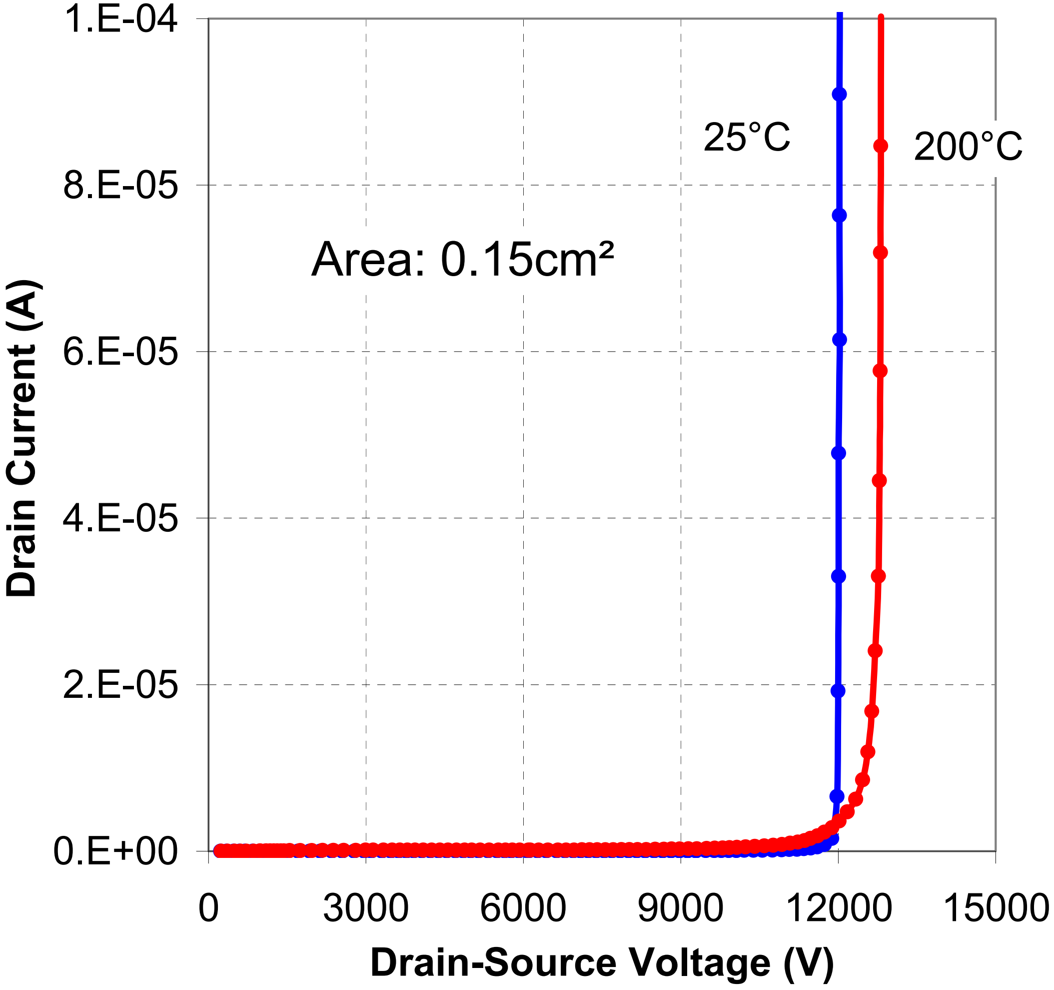
Silicon IGBT: 4.5 kV, 2us



1us /div

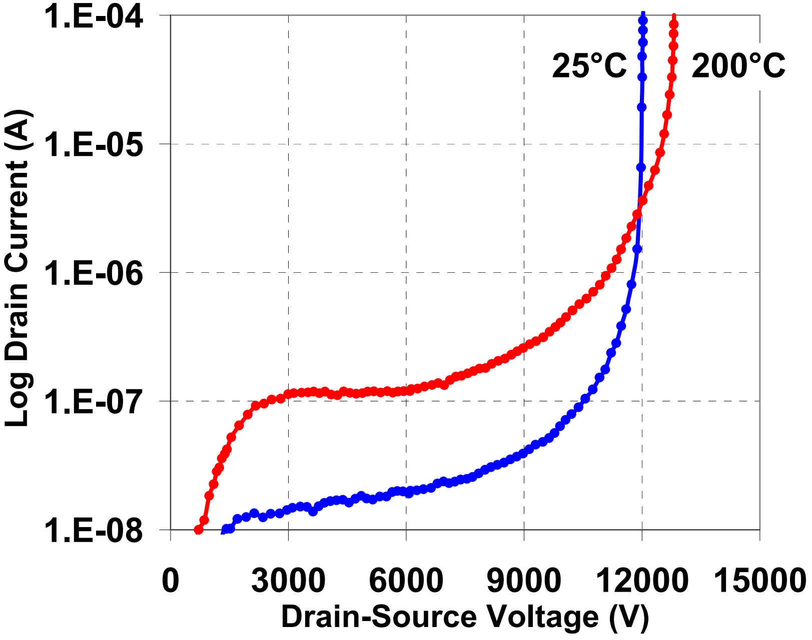
MOSFET Voltage Capability

Voltage Capability > 12 kV



Low Channel Leakage for Vg ≤ 0, T ≤ 200° C

Increased Threshold Voltage

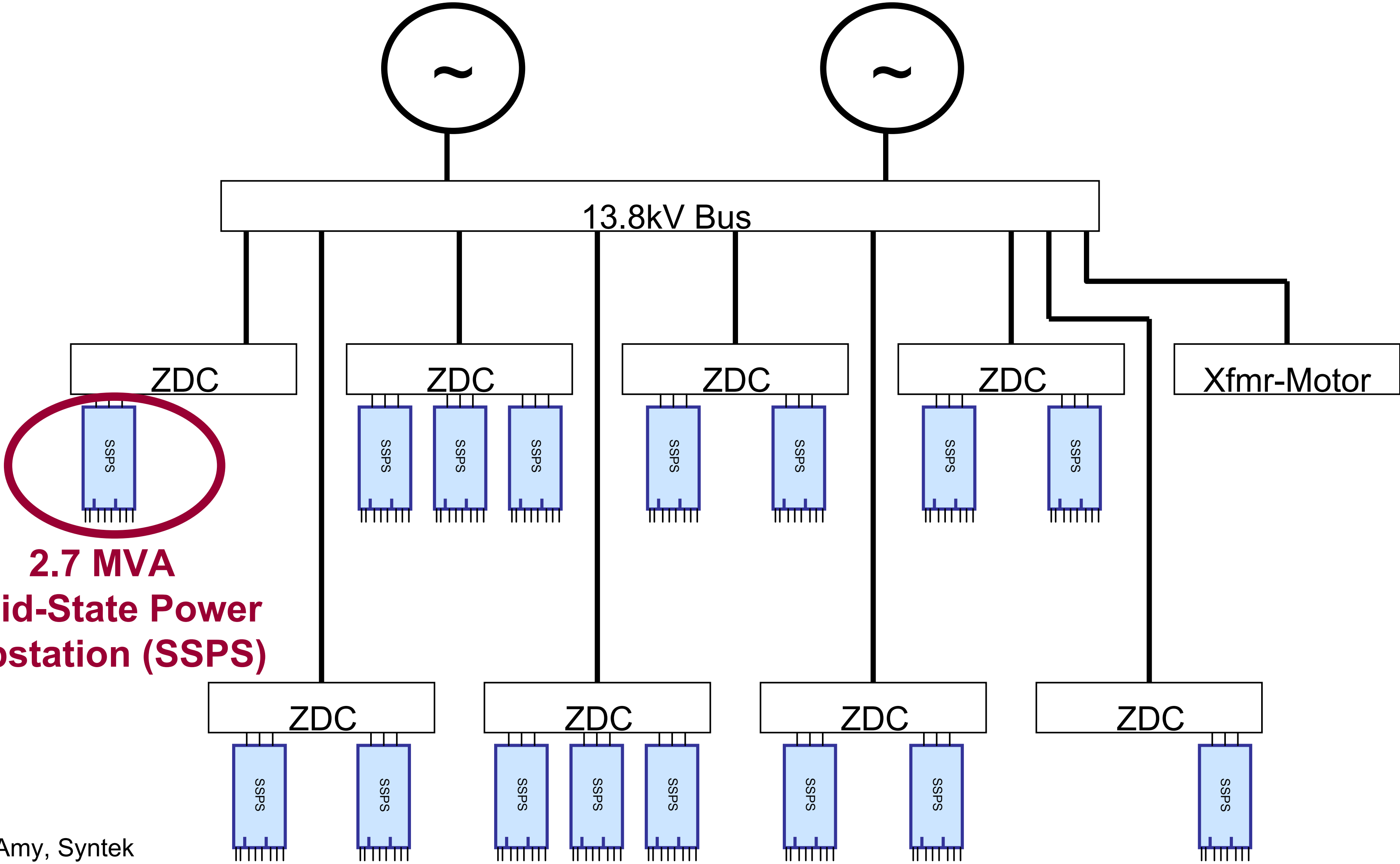


Outline

- HV-HF SiC Power Devices
- DARPA HPE Program Overview
  - Goal: Solid State Power Substation (SSPS)
  - Status: 10 kV, 100 A, 20 kHz power modules
- Component Modeling and Circuit Simulation
- Impact on Grid-Connected Power Converters

HPE Program Application

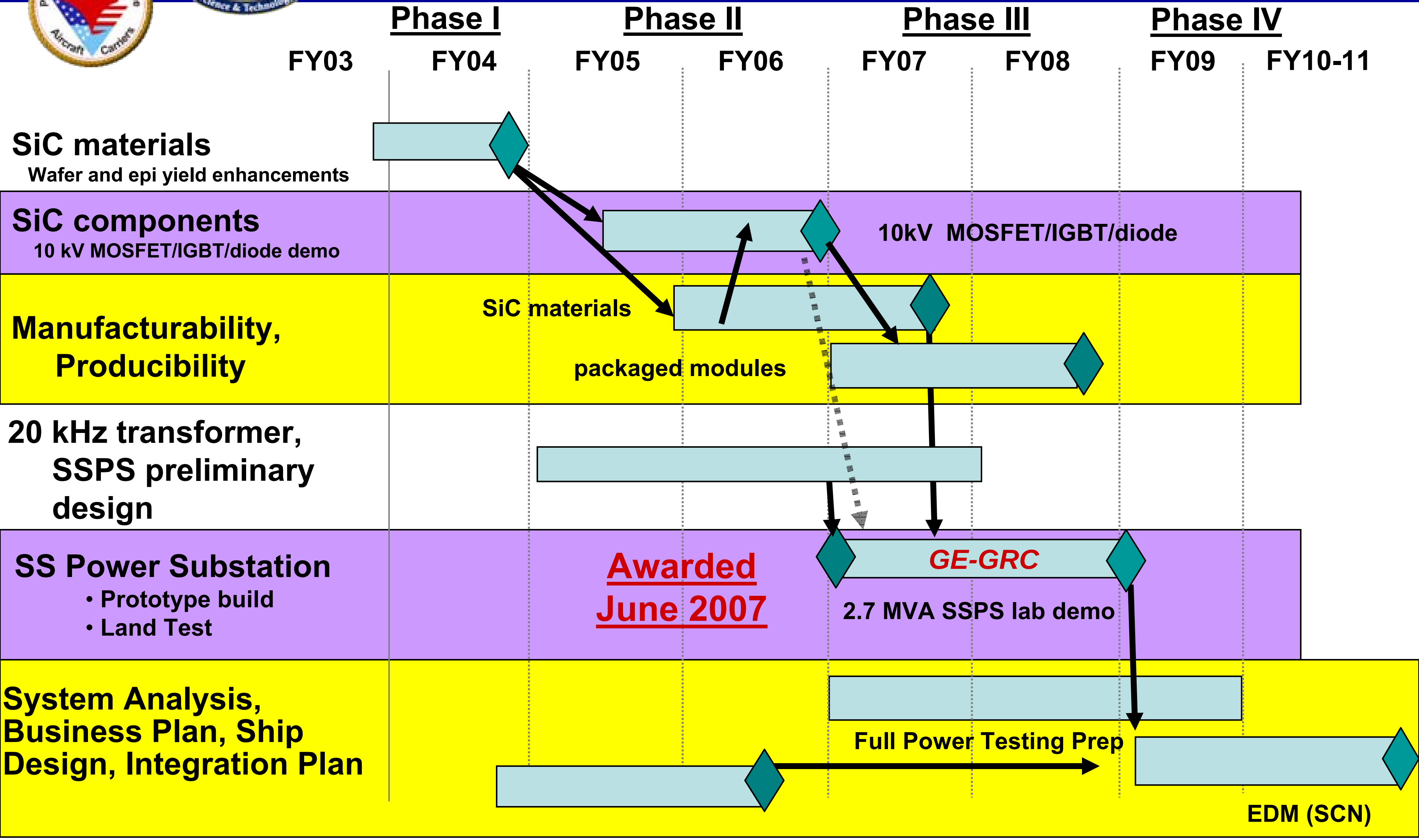
CVN21 Aircraft Carrier Zonal Distribution System



2.7 MVA Solid-State Power Substation (SSPS)

John Amy, Syntek

HPE Program Timeline



Phase I | **Phase II** | **Phase III** | **Phase IV**

FY03 FY04 FY05 FY06 FY07 FY08 FY09 FY10-11

SiC materials
Wafer and epi yield enhancements

SiC components
10 kV MOSFET/IGBT/diode demo

10kV MOSFET/IGBT/diode

Manufacturability, Producibility

SiC materials

packaged modules

20 kHz transformer, SSPS preliminary design

SS Power Substation

- Prototype build
- Land Test

Awarded June 2007

GE-GRC

2.7 MVA SSPS lab demo

System Analysis, Business Plan, Ship Design, Integration Plan

Full Power Testing Prep

EDM (SCN)

Sharon Beermann-Curtin, DARPA MTO

DARPA HPE SiC Devices

- **HV-HF SiC power devices:**

  "game changer" enabling SSPS

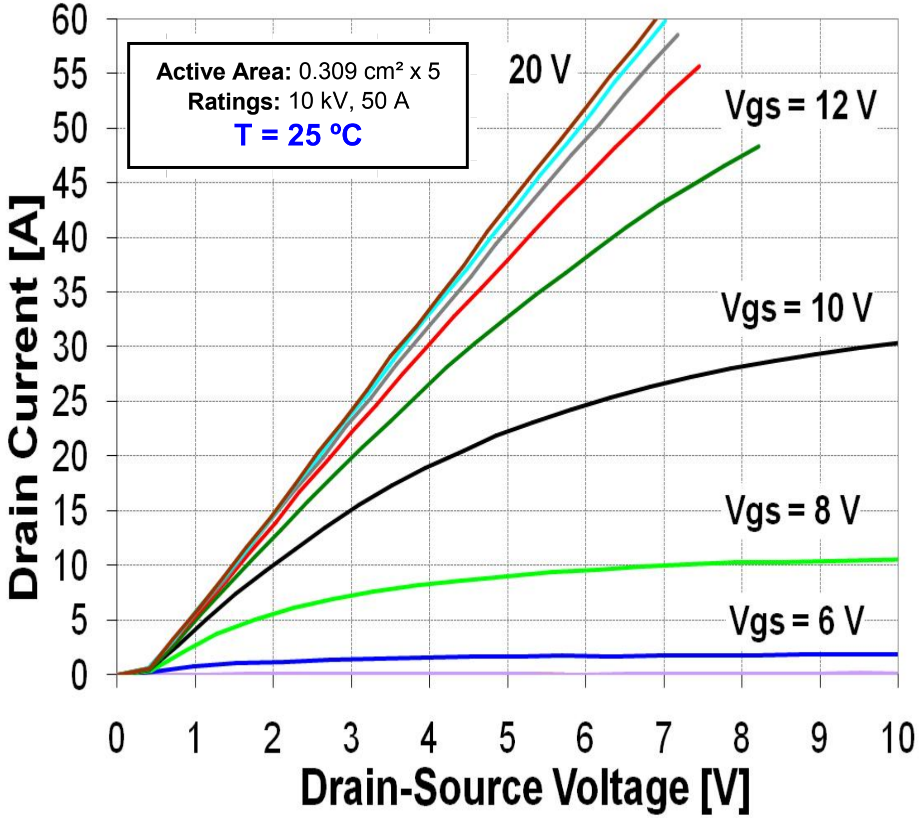
- **HPE Phase II device and module goals:**

DARPA High Power Electronics Proposed Device Development

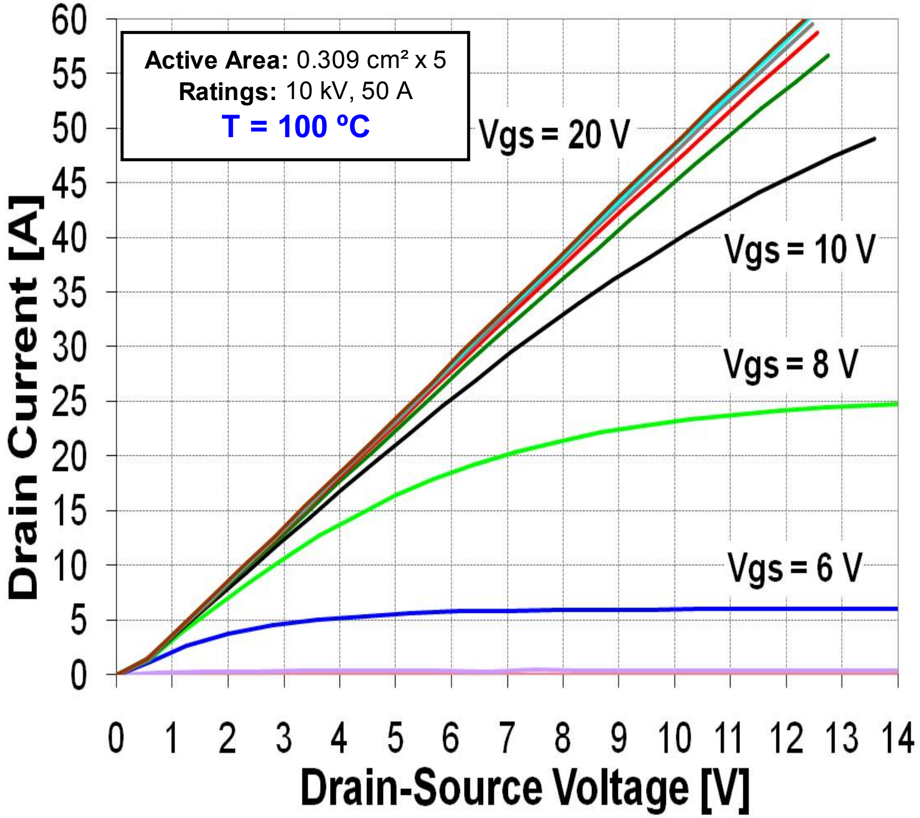
	PiN, *(JBS)* (single die)	**MOSFET** (single die)	*IGBT** *(single die)*	**Half Bridge Module**
BV (V)	**10 kV**	**10 kV**	*15 kV**	**10 – 15 kV**
Ion (A)	**45 A** *(18 A)*	**18 A**	*25 A*	**110 A**
Tj (°C)	**200 C**	**200 C**	*200 C*	*200 C*
Fsw (Hz)	**20 kHz**	**20 kHz**	*20 kHz*	**20 kHz**

Measured Output Characteristics for 50 A, 10 kV SiC MOSFET Module

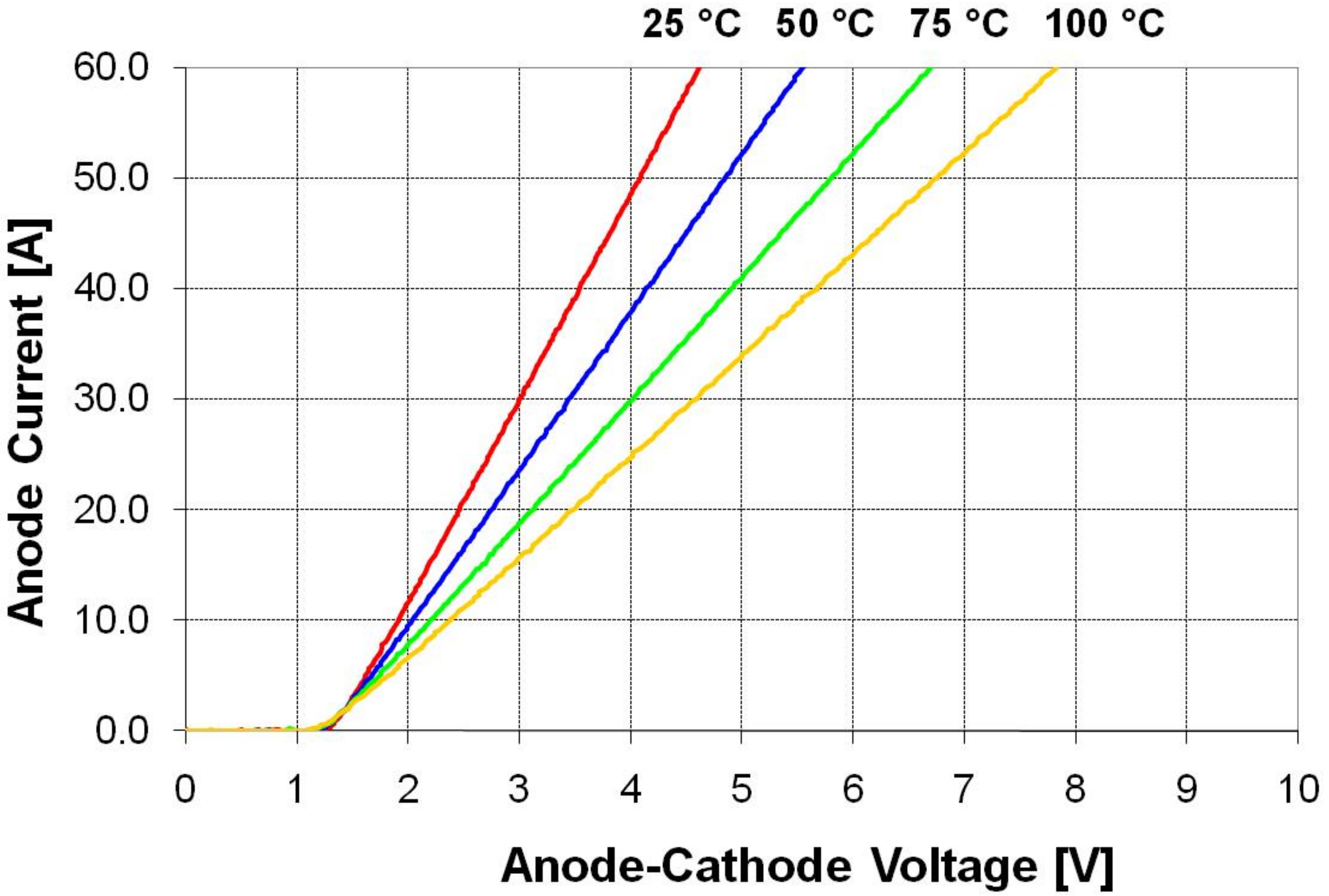
25 °C



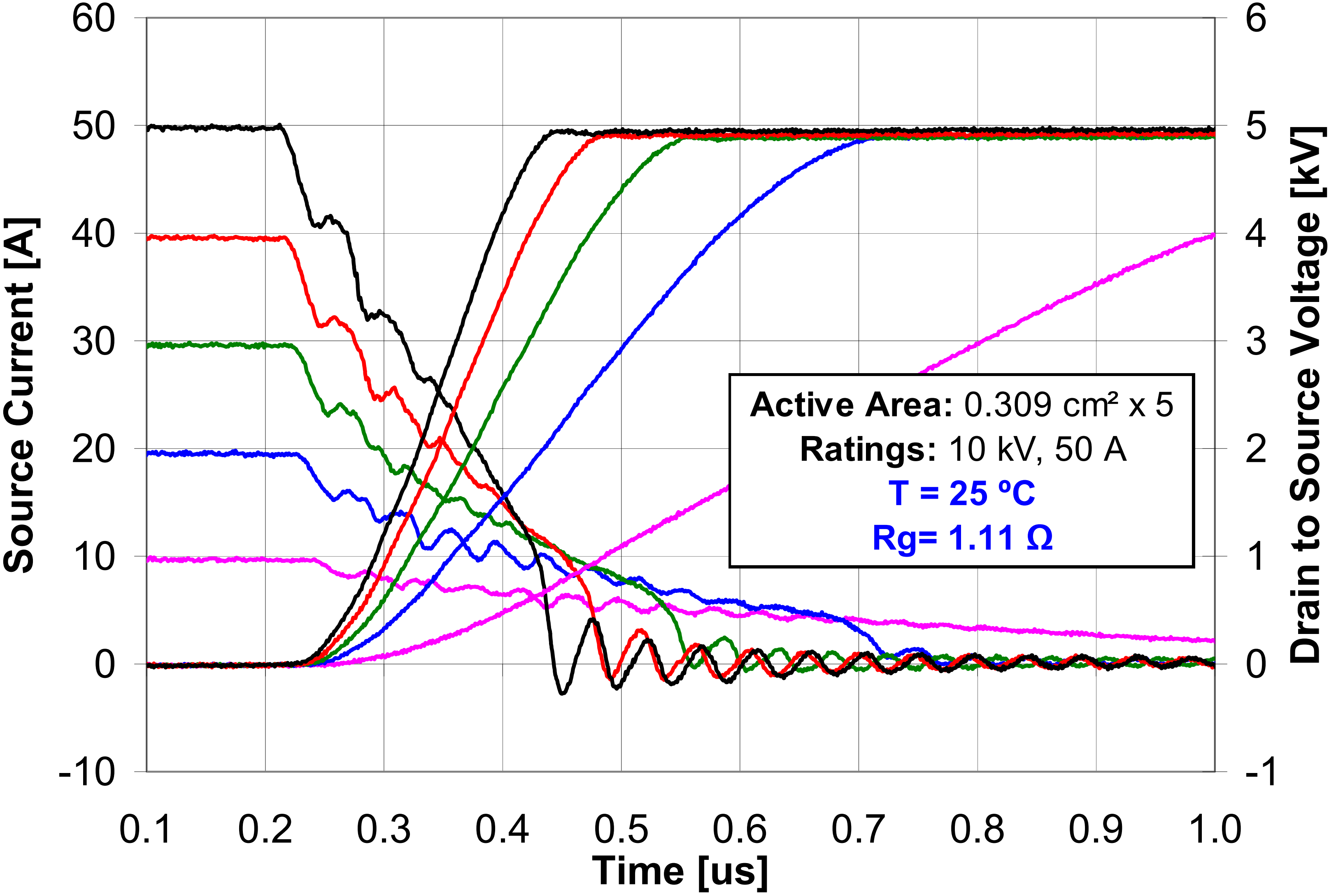
100 °C



Measured SiC JBS Diode Characteristics for 50 A, 10 kV Half-Bridge Module



Inductive Load Turn-Off for 50 A, 10 kV Half-Bridge Module



Active Area: 0.309 cm² x 5

Ratings: 10 kV, 50 A

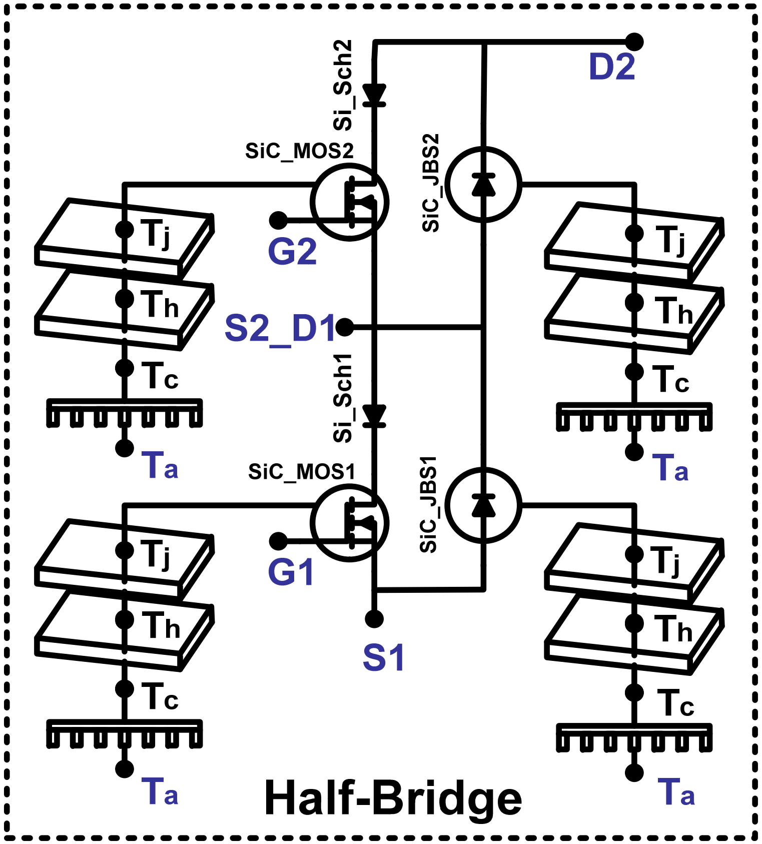
T = 25 °C

Rg= 1.11 Ω

Outline

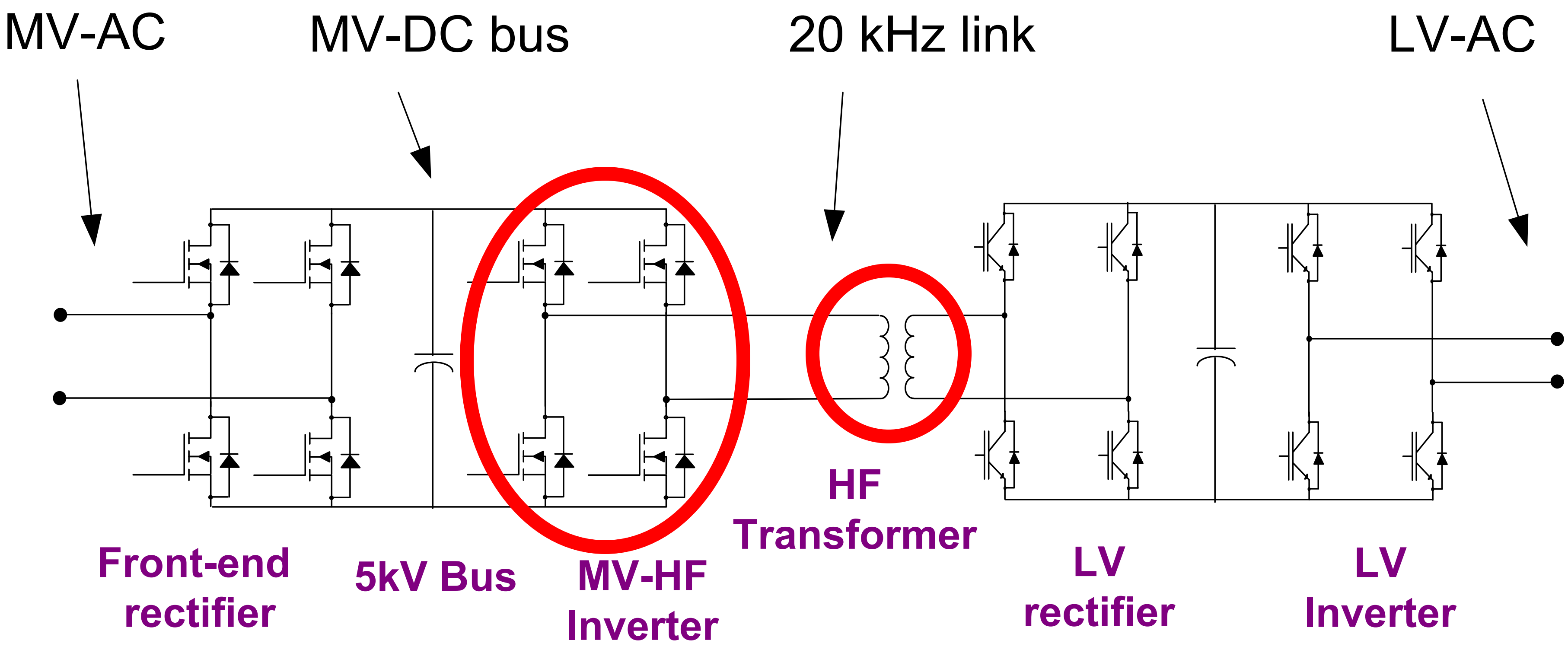
- HV-HF SiC Power Devices
- DARPA HPE Program Overview
  - Goal: Solid State Power Substation (SSPS)
  - Status: 10 kV, 100 A, 20 kHz power modules
- Component Modeling and Circuit Simulation
- Impact on Grid-Connected Power Converters

SiC MOSFET/JBS Half-Bridge Module Model and Circuit Simulation



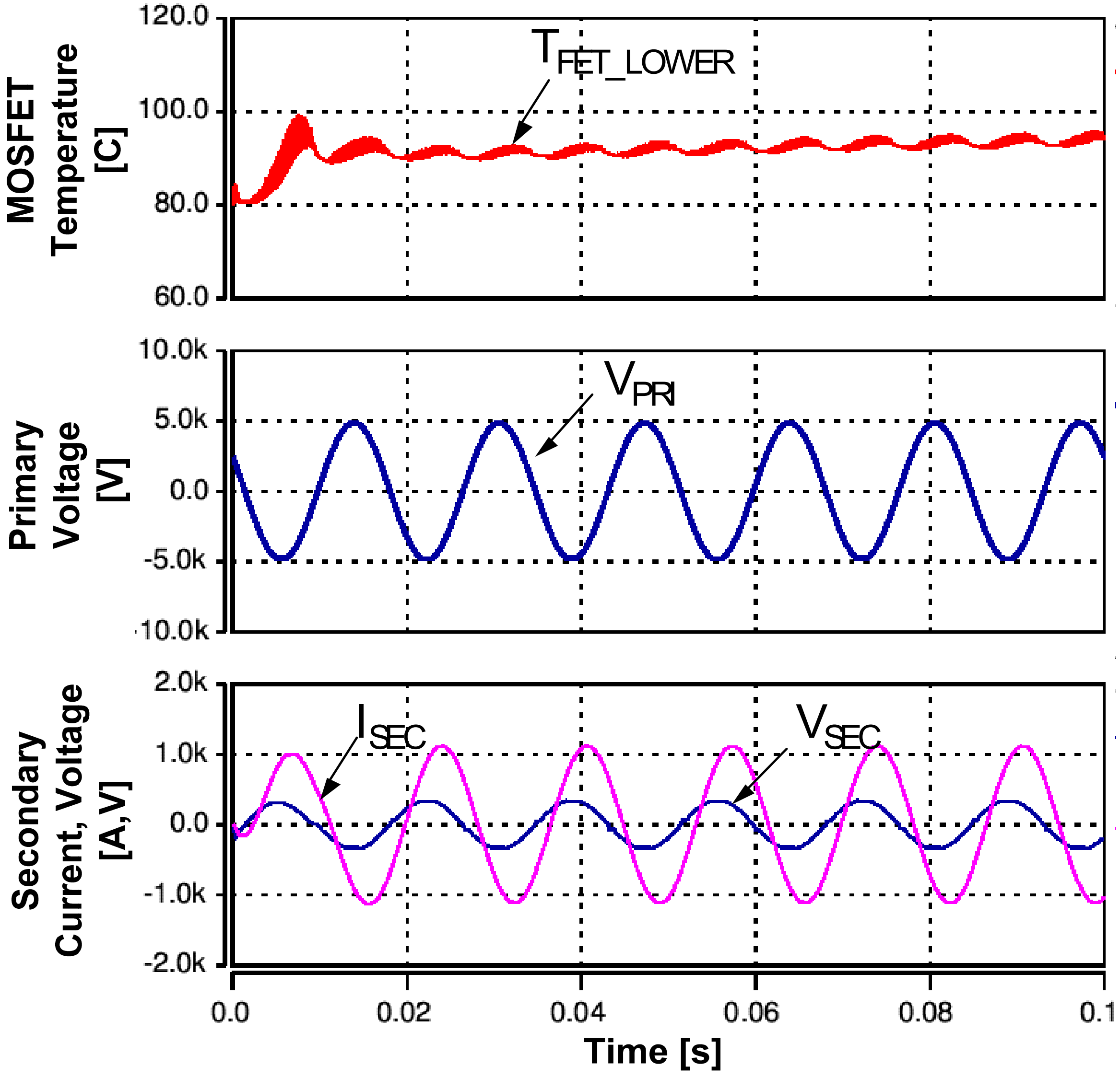
- Model being used to perform simulations necessary to:
  - optimize module parameters
  - determine gate drive requirements
  - SSPS system integration
  - impact on grid power converters
- Half-bridge module model:
  - 10 kV SiC power MOSFETs
  - 10 kV SiC JBS for anti-parallel diodes
  - low-voltage Si Schottky diodes
  - voltage isolation and cooling stack
- Validated models scaled to 100 A, 10 kV half bridge module

Representative SSPS Topology



This configuration would require twelve blocks to implement a three-phase 2.75 MVA, 13.8 kV to 465 V SSPS.

Electro-Thermal SSPS Simulation



- **Optimized module with AMOSFET = 3 cm^2 and AJBS = 2 cm^2**
- **Worst case coolant temperature of 80 ºC**
- **Rated load at 0.8 power factor lagging**
- **MOSFET temperature rises by 20 ºC to 100 ºC at start-up**

Outline

- **HV-HF SiC Power Devices**
- **DARPA HPE Program Overview**
  - **Goal: Solid State Power Substation (SSPS)**
  - **Status: 10 kV, 100 A, 20 kHz power modules**
- **Component Modeling and Circuit Simulation**
- **Impact on Grid-Connected Power Converters**

Impact on Grid Power Converters

Objective:

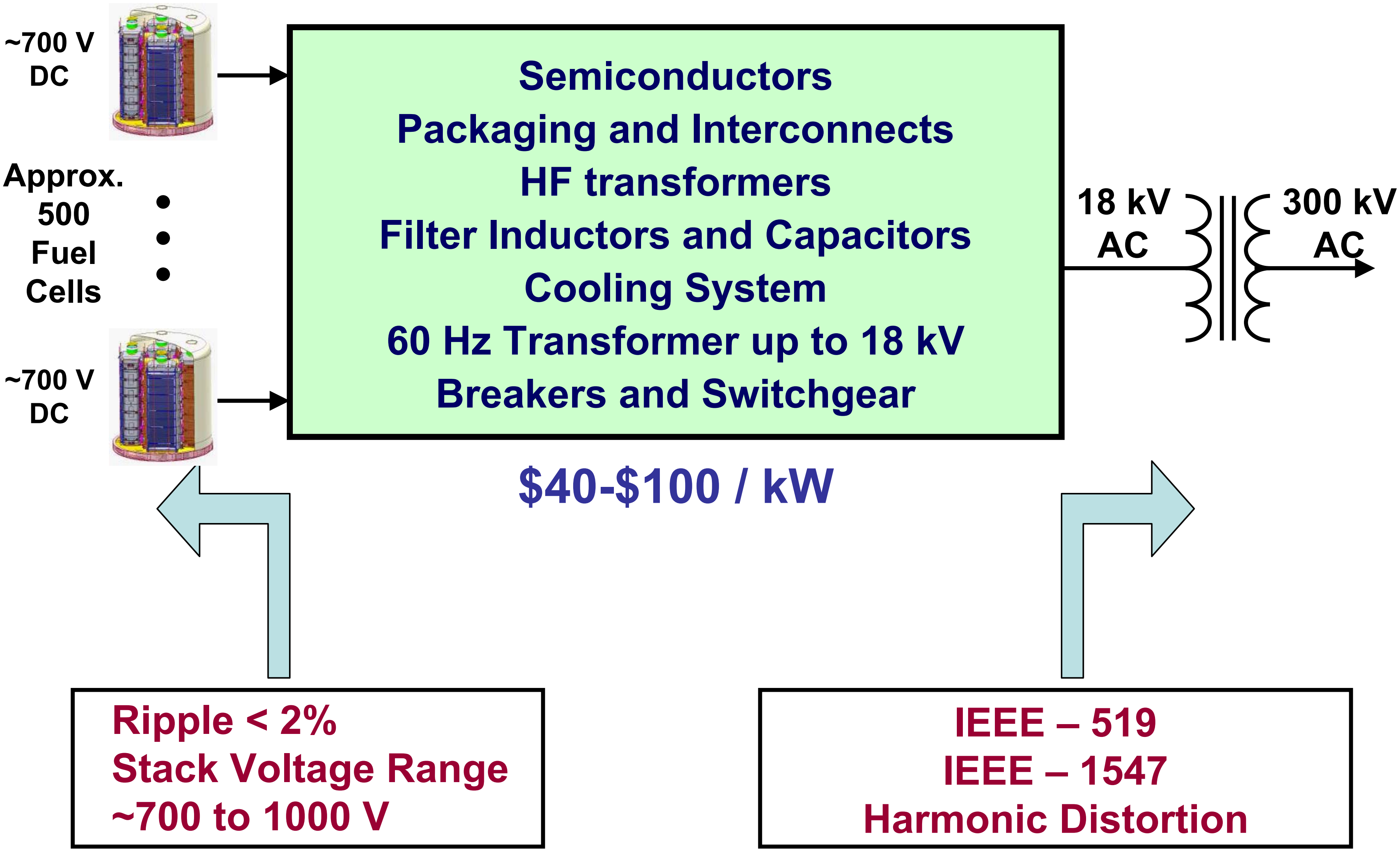
- **High-Megawatt Power Conditioning Systems (PCS) are required to convert:**
  - from power produced by Fuel Cells (FC) in future power plants
  - to very high voltage and power required for delivery to the grid

Motivation:

- **DoE SECA cost goals:**
  - FC generator plant $400/kW
  - including $40-100/kW for PCS
- **Today's PCS cost *(Fuel Cell Energy Inc.)*:**
  - FC generator plant $3,000/kW
  - including $260/kW for power converter (to 18 kV AC)

http://www.netl.doe.gov/publications/proceedings/07/SECA_Workshop/index.html

300 MW PCS



~700 V DC

Approx. 500 Fuel Cells

~700 V DC

Semiconductors
Packaging and Interconnects
HF transformers
Filter Inductors and Capacitors
Cooling System
60 Hz Transformer up to 18 kV
Breakers and Switchgear

18 kV AC

300 kV AC

$40-$100 / kW

Ripple < 2%
Stack Voltage Range
~700 to 1000 V

IEEE – 519
IEEE – 1547
Harmonic Distortion

Advanced Technology Cost

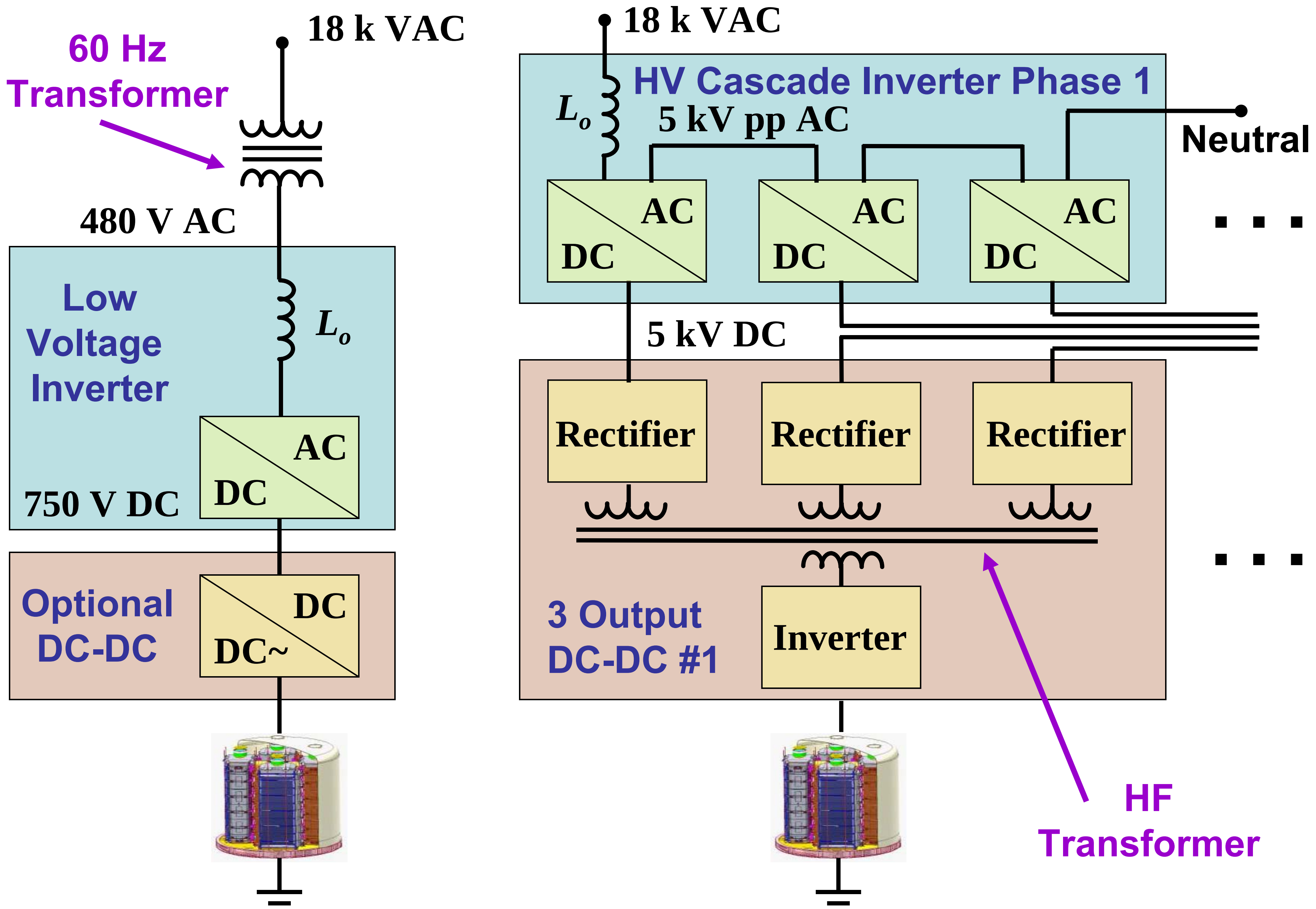
- Future, high-volume costs: 5 to 10 years, 1 GW/yr

- Advanced Technology Goals and Cost Break Points
  - 1.2 kV Schottky diodes: $0.2/A
  - 12 kV Schottky diodes: $1/A
  - 12 kV Half-bridge SiC-MOSFET/SiC-Schottky: $10/A
  - 15 kV SiC-PiN: $0.4/A
  - 15 kV SiC-IGBT/SiC-PiN Module: $3.3/A
  - Nano-crystalline transformer: $2/kW
  - Power Electronics DC-DC, DC-AC: 150 % overhead
  - 60Hz Transformer and Switchgear: 50 % overhead

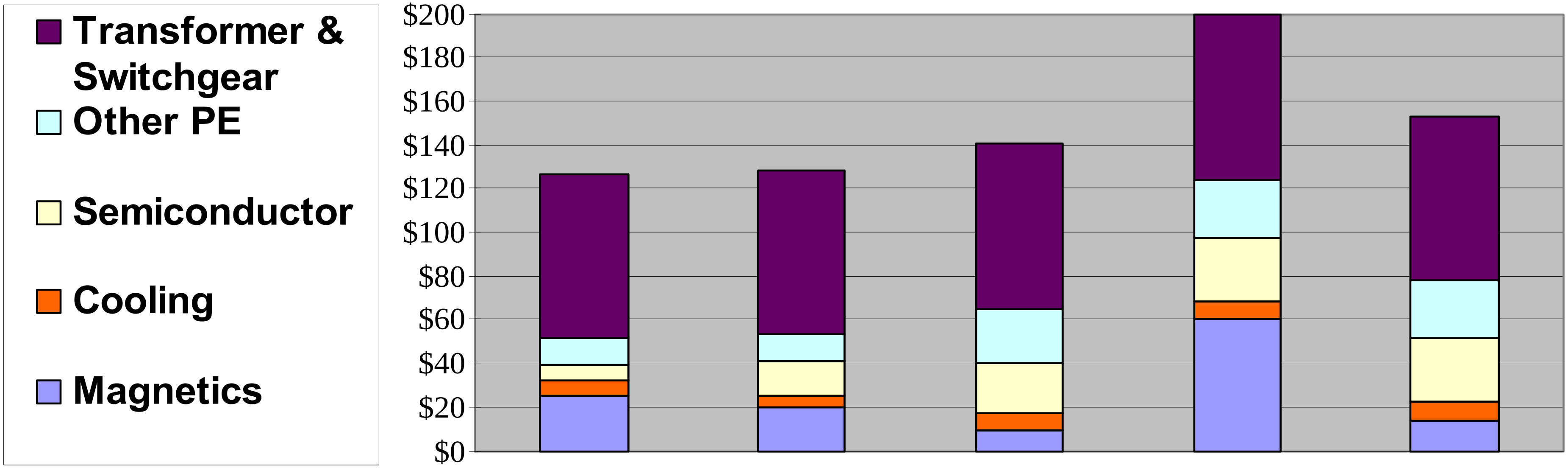
Power Converter Architectures

- **Low-Voltage Inverters (460 V AC):**
  - Require high inverter current for each FC module
  - and large number of Inverters for 300 MW Plant
- **Medium-Voltage Inverters (4160 V AC):**
  - Lower inverter current for each FC module
  - Combine multiple FCs with single high power inverter
- **High-Voltage Inverters (18 kV AC):**
  - Replaces 60 Hz transformer with isolation from HF transformer
  - Cascade enables: 18 kV AC inverter by series connection, and interleaved switching decreases losses and filter requirement

HF Transformer versus 60 Hz Transformer



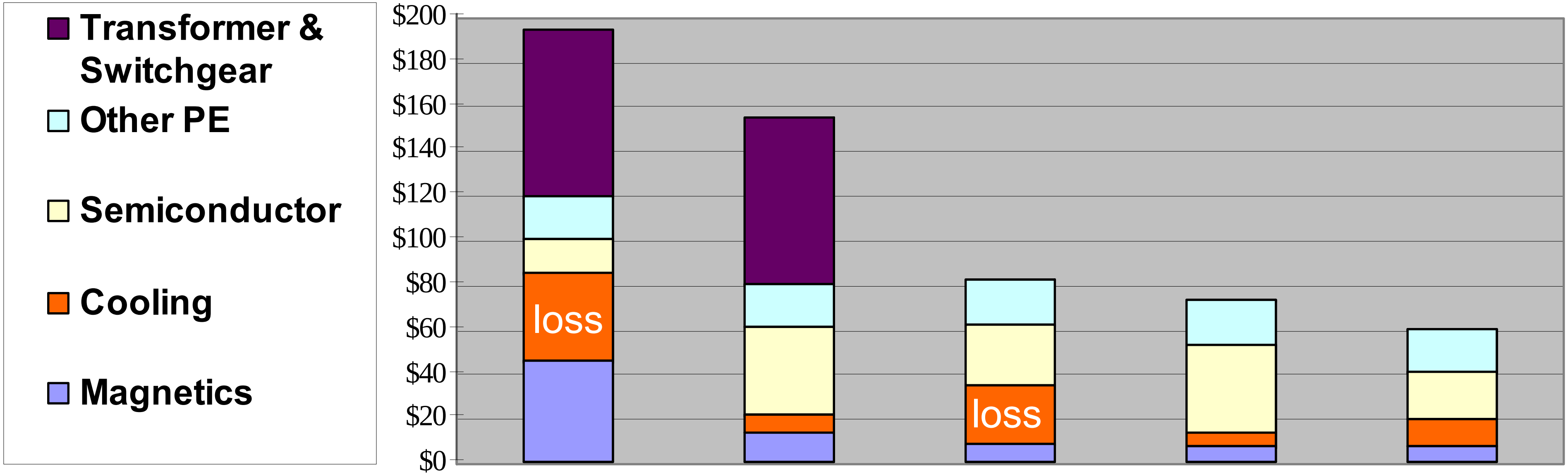
Estimated $/kW: LV Inverter



Inverter Voltage	Low	Low	Low	Low	Low
Converter Stages	One	One	Two	Two	Two
LV-SiC Schottky		yes	yes	yes	yes
HF Transformer				Ferrite	Nano
60 Hz Transformer	yes	yes	yes	yes	yes

Risk Level: Low | Moderate | Considerable | High

Estimated $/kW: MV & HV Inverter



Inverter Voltage	Medium	Medium	High	High	High
HV-SiC Diode		Schottky	Schottky	Schottky	PiN
HV-SiC Switch		MOSFET		MOSFET	IGBT
HF Transformer	Nano	Nano	Nano	Nano	Nano
60 Hz Transformer	yes	yes			

Risk Level: Low Moderate Considerable High

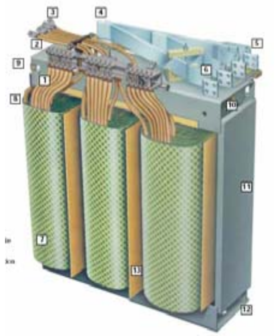
Conclusion

- HV-HF switch-mode power conversion:
  - SiC material enables HV-HF devices
  - efficiency, control, functionality, size and weight,… cost
- DARPA HPE SiC devices reduce weight for CVN21
  - Phase II is developing 100 A, 10 kV SiC power modules
  - Phase III goal is 13.8 kV 2.7 MVA Solid State Power Substation
- Circuit simulation used to
  - Optimize SiC module and system
  - Evaluate impact of new technology on grid power converters
- SECA goal of $40-$100 / kW for the fuel cell plant
  - High-Voltage grid-connected inverter may reduce cost
  - Requires HV-HF SiC devices and HF power transformer

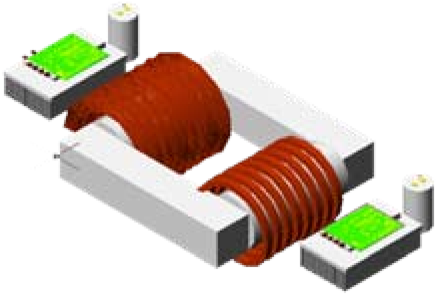
SiC Benefits and Requirements

Voltage and Current Range				
BV (kV)	0.3 – 1.2 kV	2 – 6 kV	10 – 15 kV	20 – 40 kV
Ion (A)	1 - 500 A	50 – 3000 A	3 – 1000 A	200 A
Si Speed	20ns PiN	<1k - 15kHz	---	---
SiC Speed	0ns Schottky	> 20 kHz	50ns, 20 kHz	> 1 kHz
SiC Benefits	Efficiency *High Temp HT Coolant	Efficiency Control	Control Functionality Weight	Control Functionality Part Count
SiC Barrier	Cost *HT Package *MOS mobility/ oxide reliability	Cost Large Area/ Full-wafer-device	Vf degradation HV-HF package Yield High Volume	HV substrate Vf degradation Series Package

HPE Phase III Goal



Low Frequency Conventional Transformer (analog)
- 2.7MVA
- 13.8kV/450V (Δ/Y) 60Hz
- **6 tons/each**
- **10 m^3/each**
- **fixed, single output**



Estimated SiC-based Solid State Power Substation (digital)
- 2.7 MVA
- 13.8kV/465V (Δ/Y) 20 kHz
- **1.7 tons/each**
- **2.7 m^3/each**
- **multiple taps/outputs**

BENEFITS:
- **Reduction of weight and volume**
- **Precise voltage regulation to isolate voltage spikes, voltage dips**
- **Unity Power Factor (20% increase in power)**
- **Fast fault detection, protection, and potential removal of circuit breakers**

Sharon Beermann-Curtin, DARPA MTO

SiC Power Device and Material Technology For High Power Electronics

High Megawatt Power Technology R&D Roadmap Workshop

April 8, 2008

David Grider
Cree, Inc.
4600 Silicon Drive
Durham, NC 27703; USA
Tel:: 919-313-5345
Mobile: (919) 201-3590
Email: david_grider@cree.com

Support Provided By -
DARPA - Sharon Beermann-Curtin
ARL - Skip Scozzie
AFRL – Jim Scofield

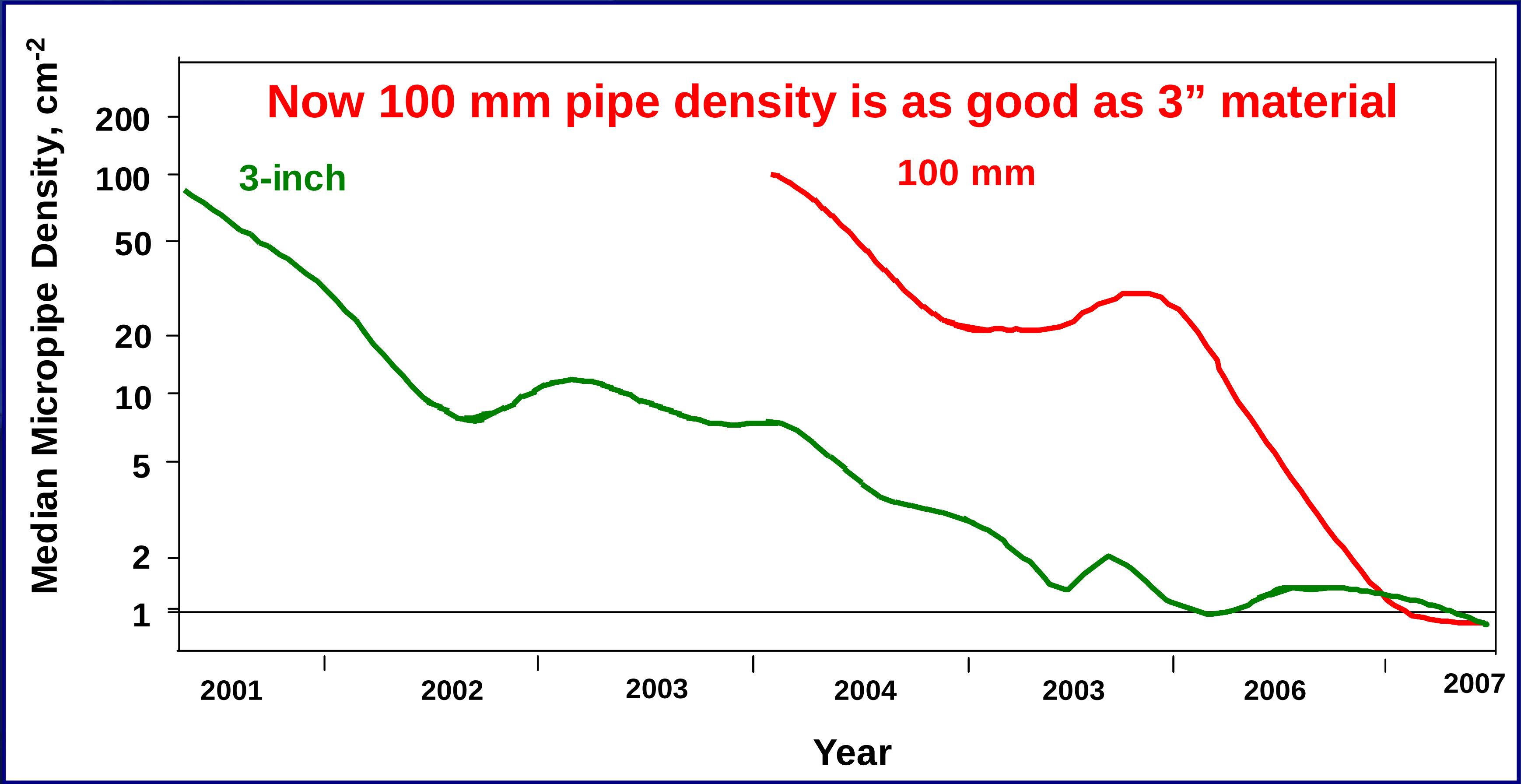
Cree Excellence in SiC Materials and WBG Device Manufacturing

Cree Corporate Headquarters
Durham, NC

- **World's Largest Fabricator of GaN-on-SiC**
  - **Ship > 15 million devices per day**
- **World's Largest Supplier of SiC substrates**
  - **Supply 95% of the world's supply of single crystal SiC**
- **Vertical Integration**
  - **Crystal Growth => Device Fabrication => Package/Test**

Dramatic Reduction in 4HN SiC Substrate Micropipe Densities

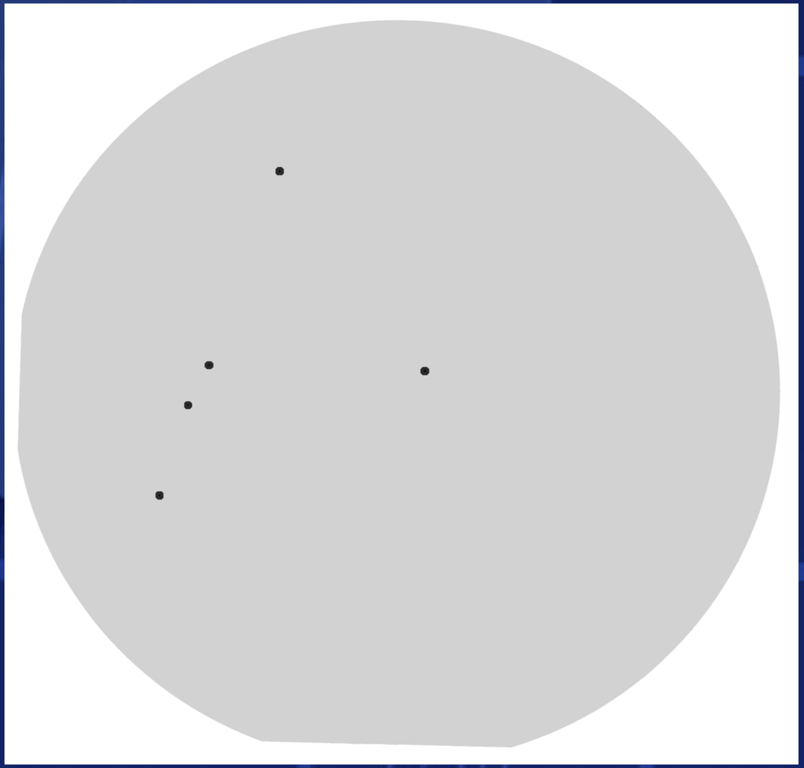
Monthly <u>median</u> micropipe density of 4H n-type wafers is < 0.8 cm^{-2}



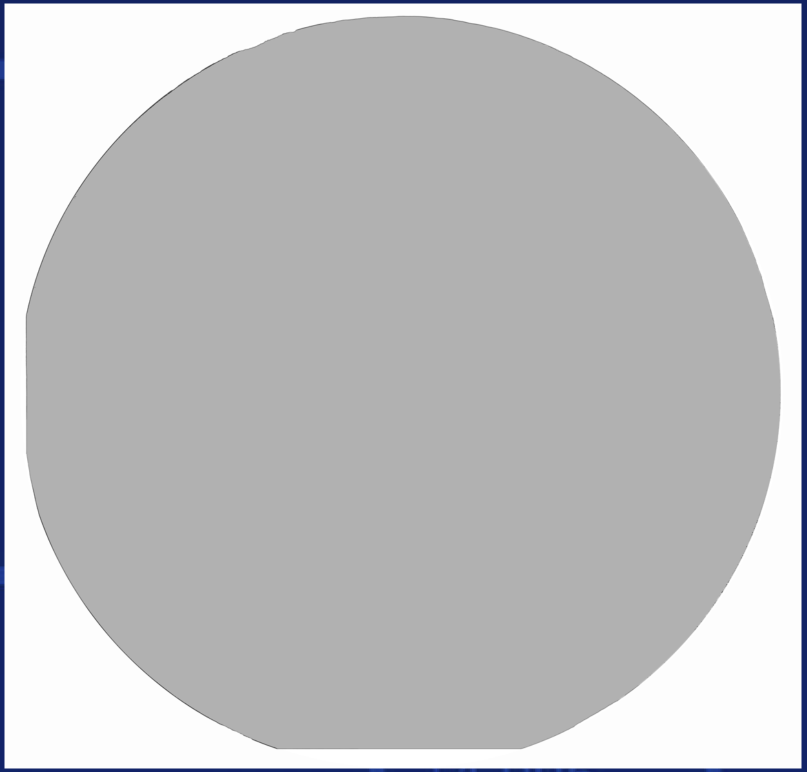
100-mm work supported by ARL MTO (W911NF-04-2-0021) and DARPA (N00014-02-C-0306)

100 mm 4HN-SiC Substrate Quality

Almost Double the Area of a 3-inch 4HN-SiC Wafer

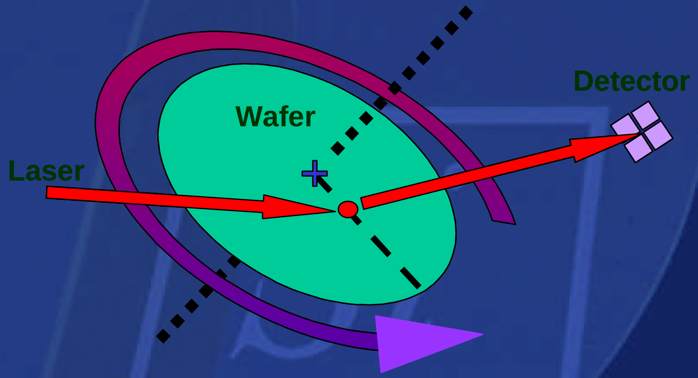


Typical 100 mm 4HN-SiC Wafer MPD ~ 0.6 cm^{-2}

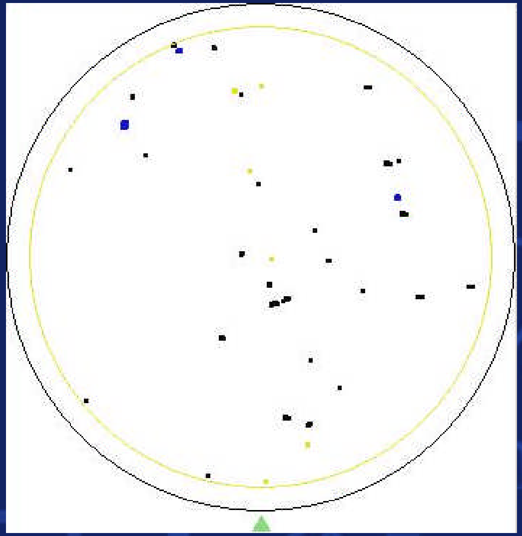


Micropipe Free 100 mm 4HN-SiC Wafer

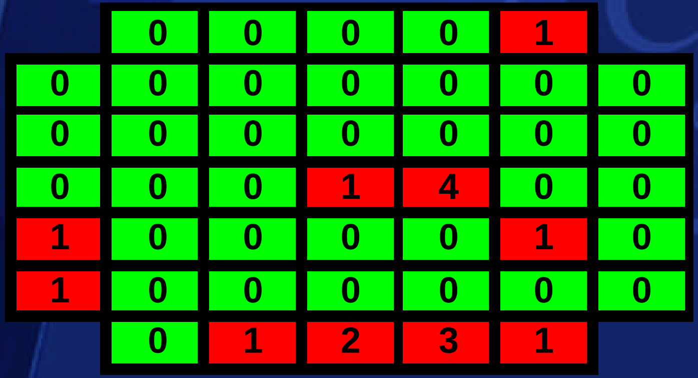
SiC Substrate and Epi Defect Mapping For Enhanced SiC Device Yield



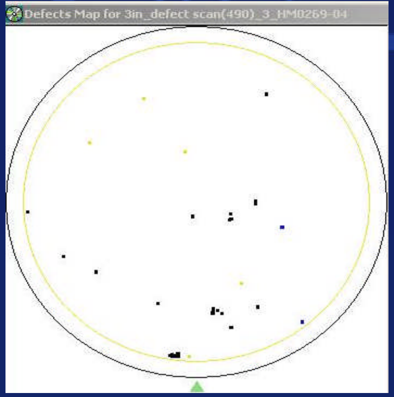
Candela Tool For Automated SiC Material Defect Mapping



- **Predicted "Material" Yield for 8x8 mm SiC JBS Diodes = 63%**
- **Measured Yield for 10.6 x 8.3 mm SiC JBS Diodes = 72%**

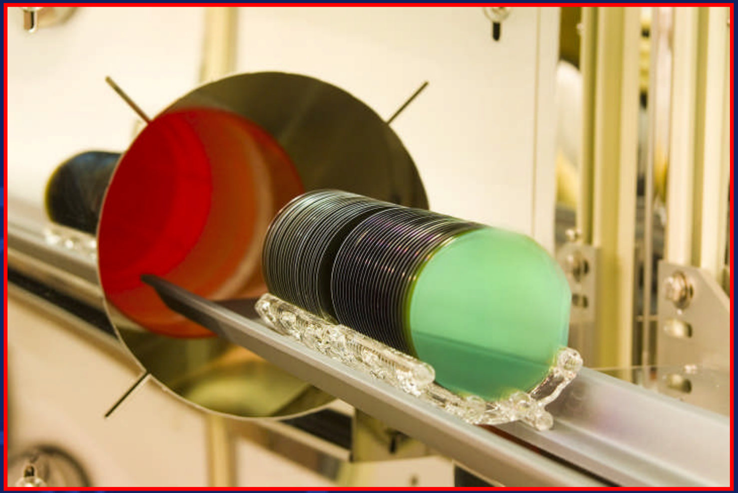


	🟩 0	🟩 0	🟩 0	🟩 0	🟥 1	
🟩 0	🟩 0	🟩 0	🟩 0	🟩 0	🟩 0	🟩 0
🟩 0	🟩 0	🟩 0	🟩 0	🟩 0	🟩 0	🟩 0
🟩 0	🟩 0	🟩 0	🟥 1	🟥 4	🟩 0	🟩 0
🟥 1	🟩 0	🟩 0	🟩 0	🟩 0	🟥 1	🟩 0
🟥 1	🟩 0	🟩 0	🟩 0	🟩 0	🟩 0	🟩 0
	🟩 0	🟥 1	🟥 2	🟥 3	🟥 1	



- **Predicted "Material" Yield for 8.1x8.1 mm SiC DMOSFETs = 77%**

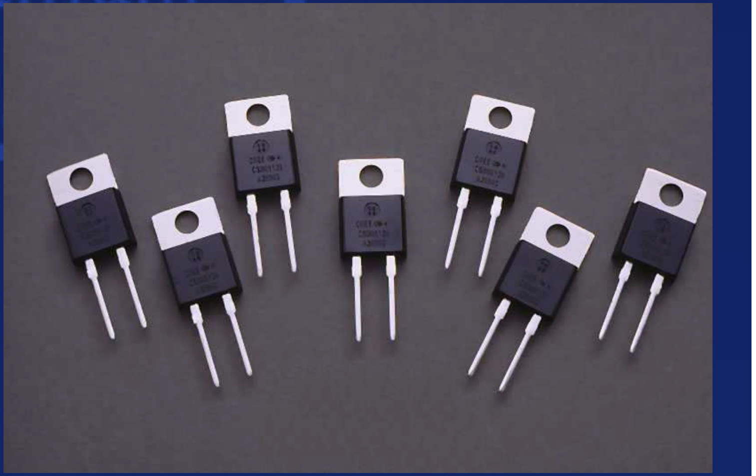
Cree WBG Technology Center of Excellence



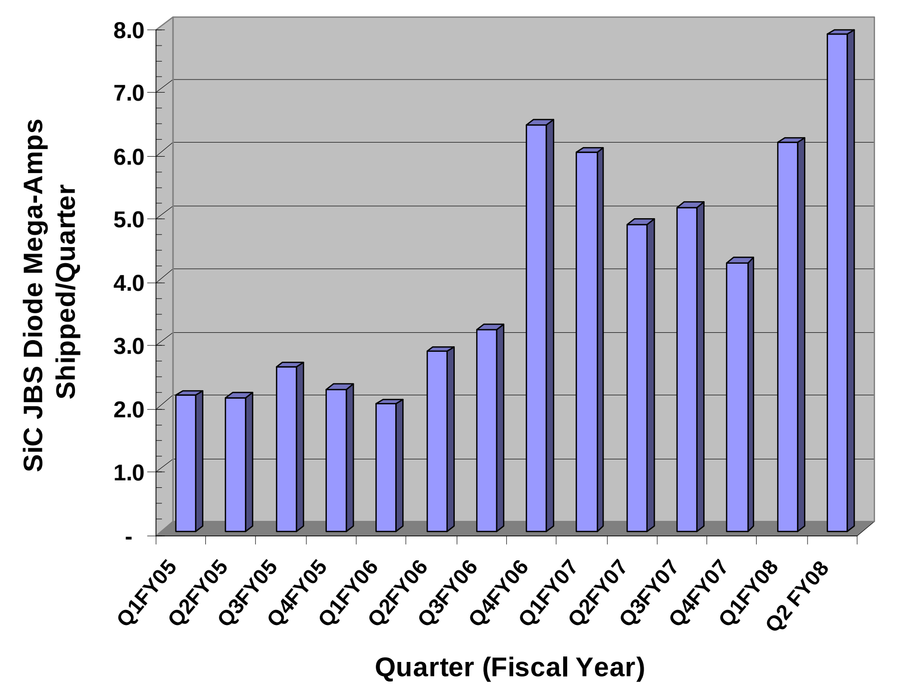
- Opened August 2006 For Large-Scale Commercial Production And Advanced Research in WBG Power and RF Products
- Located in Research Triangle Park (RTP), North Carolina
- Worlds Largest Dedicated WBG Production Device Facility
  - 40,000 total sq. ft.
  - WBG Device Fabrication Capacity: 10K Wafer Starts per Year
  - SiC Power Device Characterization & Reliability Labs
  - SiC Power On-wafer Probe and Dice
  - SiC Power Applications Support

Cree's SiC Power Product Roadmap

- SiC Power Products
  - *ZERO RECOVERY*™ Rectifiers –
    - SiC JBS Diodes
    - 300V – 10A to 20A
    - 600 V – 1A to 20A
    - 1200V - 5A to 50A
    - 10kV/10A - Product Development
  - SiC PiN Diodes
    - > 2400V - Product Development
  - SiC DMOSFETs
    - 1.2kV – 10kV / 10A - 67A
    - Product Development
  - SiC IGBTs
    - ≥ 12kV - Advanced Development

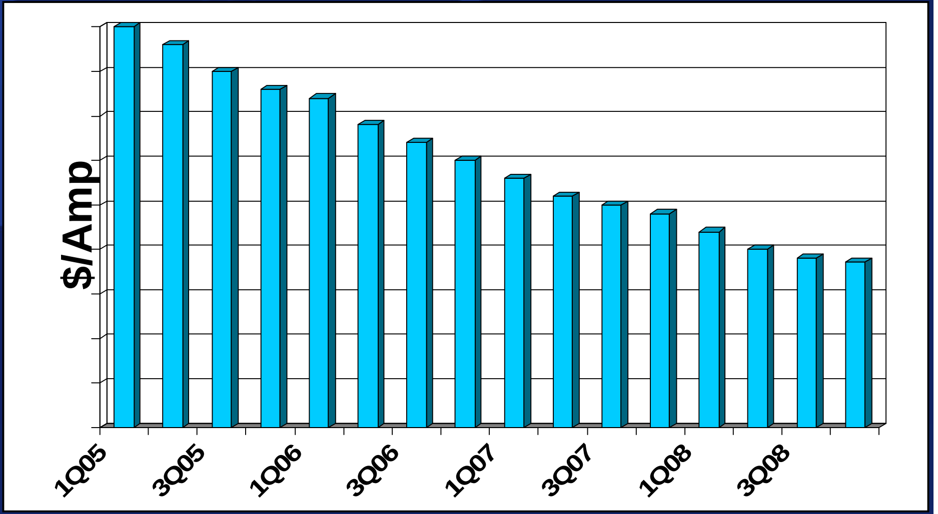


Growth in Commercial Production of SiC JBS Diodes at Cree

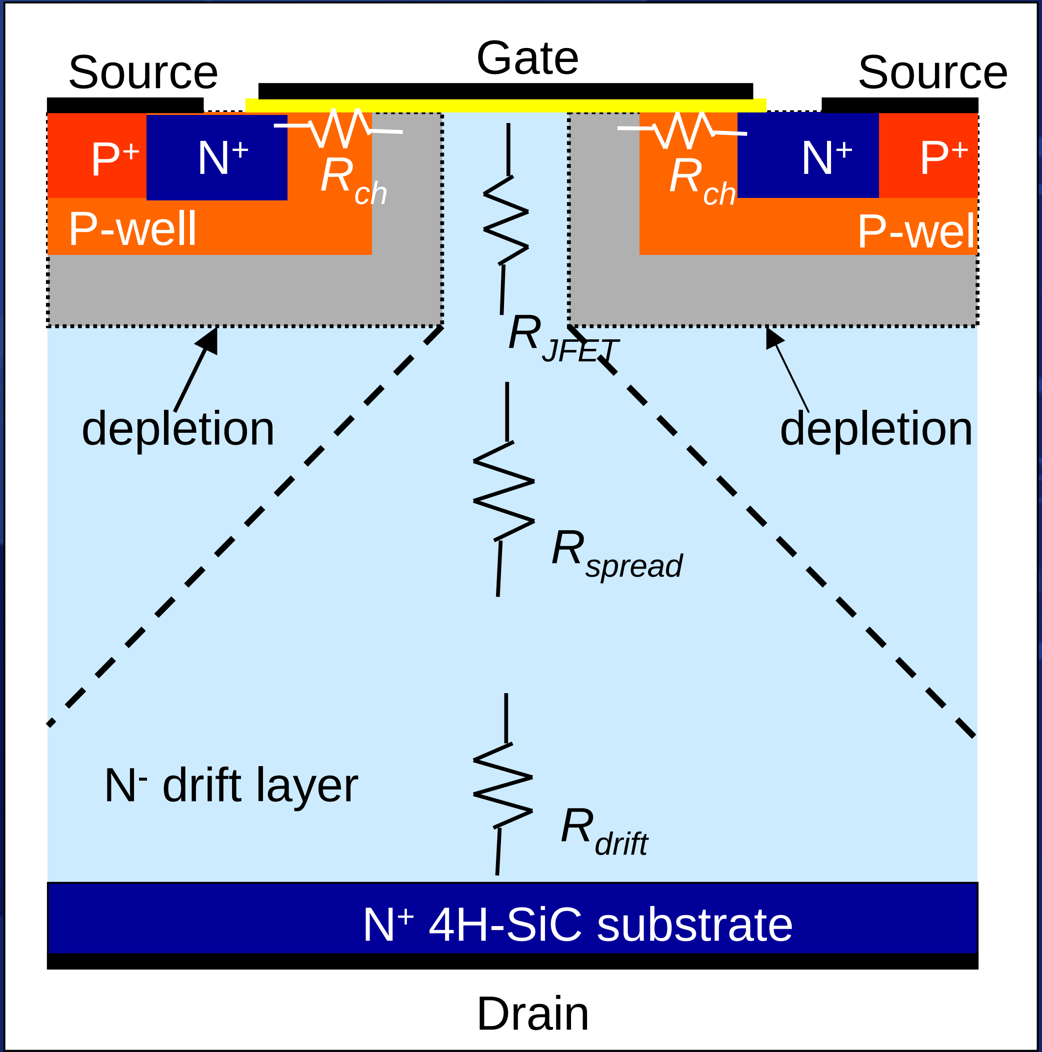


- Over 2x Reduction in Price of SiC JBS Diode – 3 Factors
  - Higher Quality SiC Material
  - Larger Production Volumes
  - Increase SiC Wafer Size From 3 inch to 100 mm Diameter

In Q2-FY08 (Ending 12/07) Cree Shipped **7.8 Mega-Amps** of SiC JBS Diodes



Double Implanted MOSFET (DMOSFET)



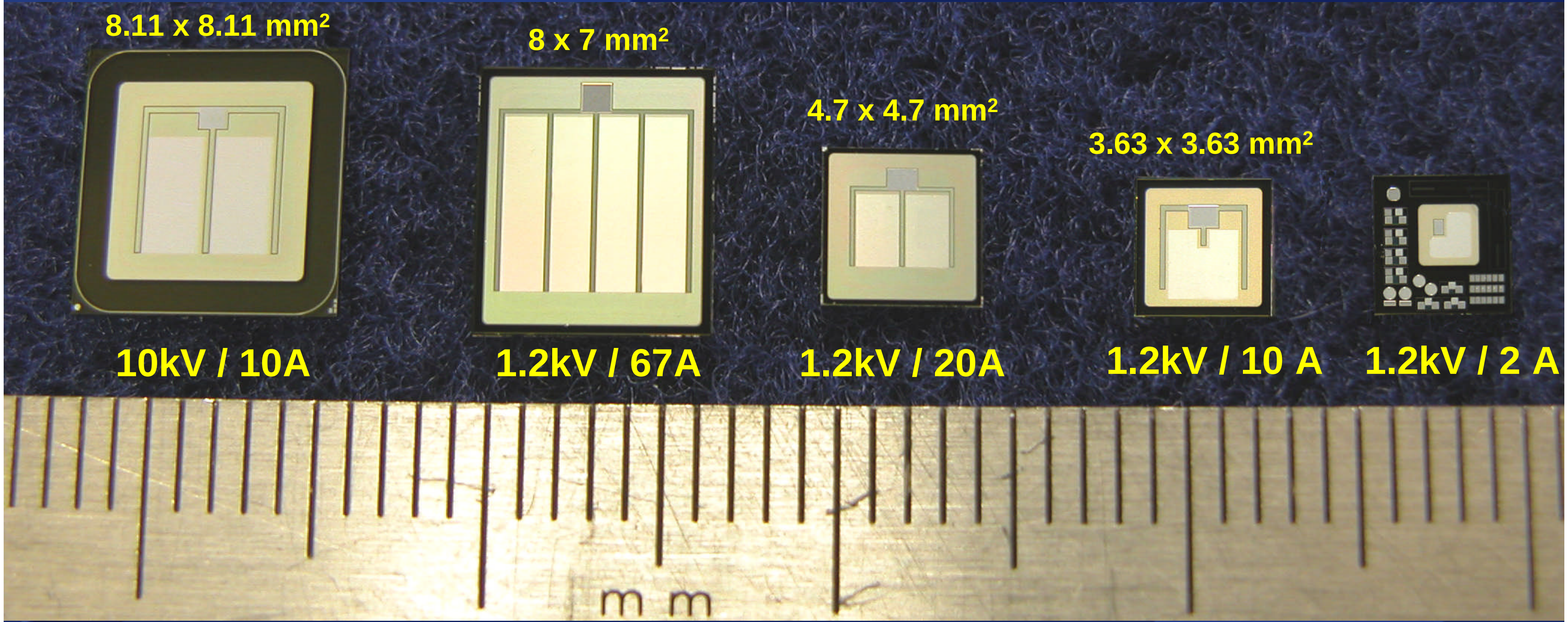
Pursuing DMOSFET
As Power Switch
From 1.2kV Up To 10kV

DMOSFET Requirements

- **Low $R_{on,sp}$**
- **High Switching Speed**
- **Manufacturable Design/Process**
- **Acceptable Reliability**

Scaling of SiC DMOSFET Technology

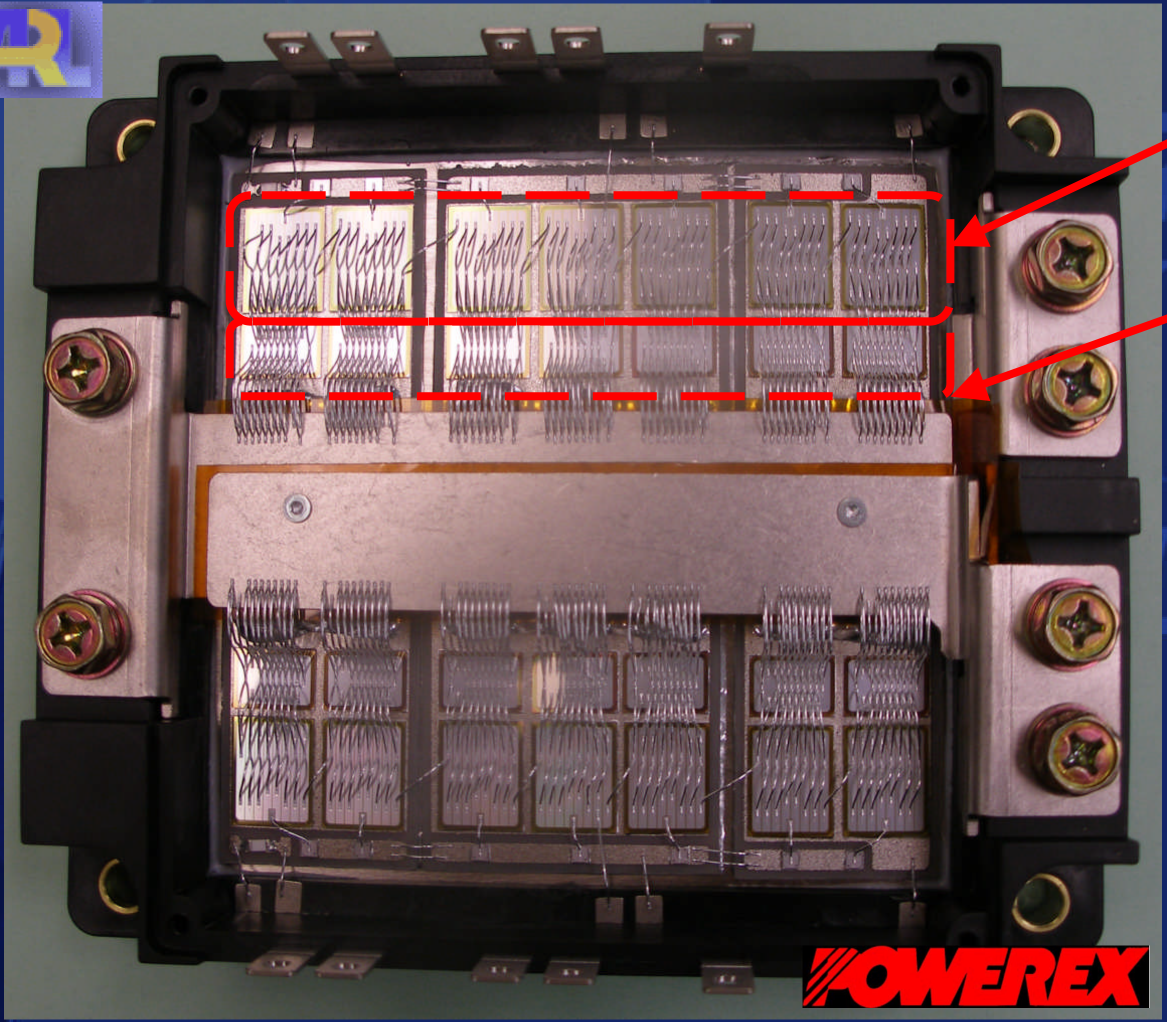
2008 ← 2004



SiC MOSFET Power Module for FCS Hybrid Electric Vehicle (HEV) Propulsion

All SiC 1.2kV / 1400A Power Module

R_G = 0.5 ohm, f = 10 kHz



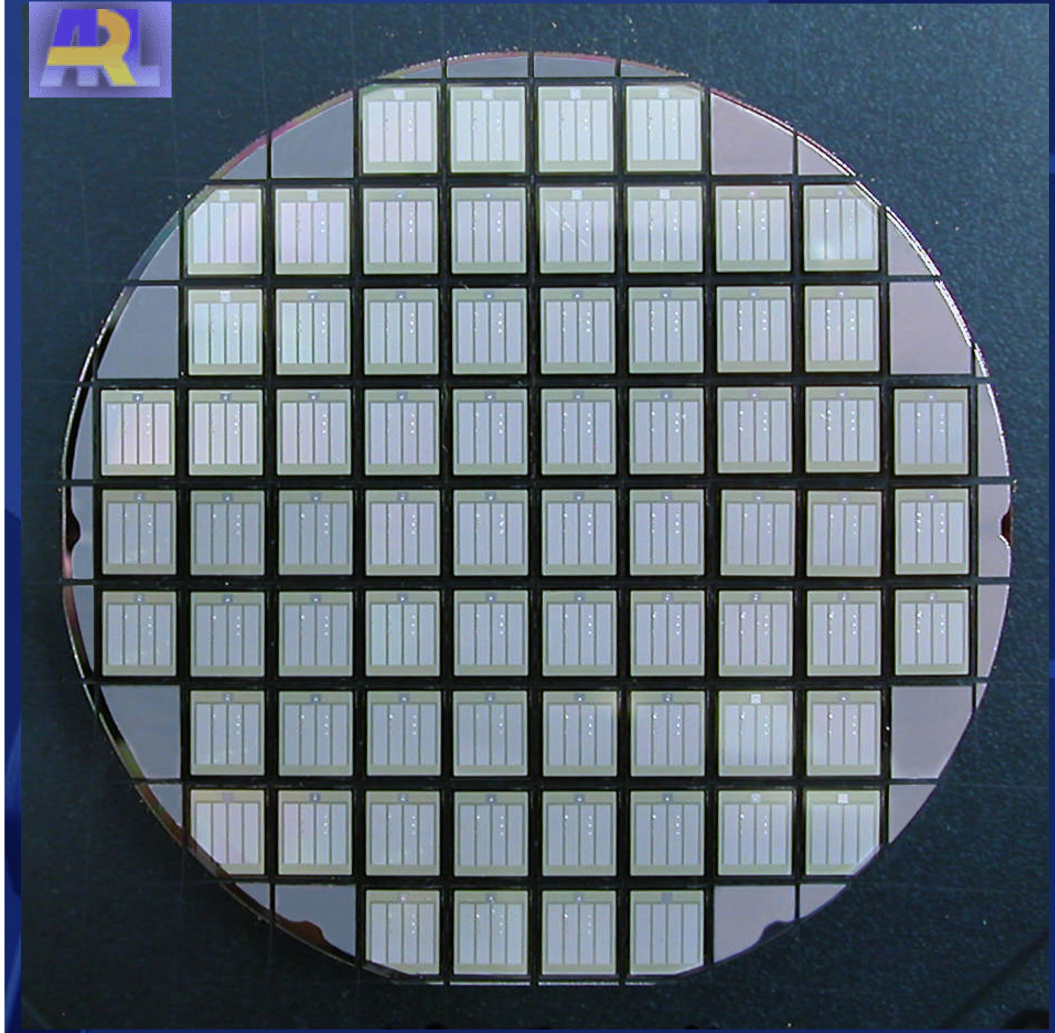
Replace Si IGBT with SiC MOSFET => 40% Reduction in Loss

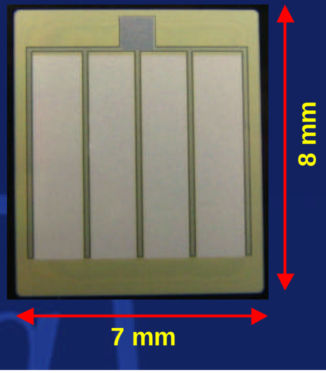
Replace Si diode with SiC JBS Diodes => 20% Reduction in Loss

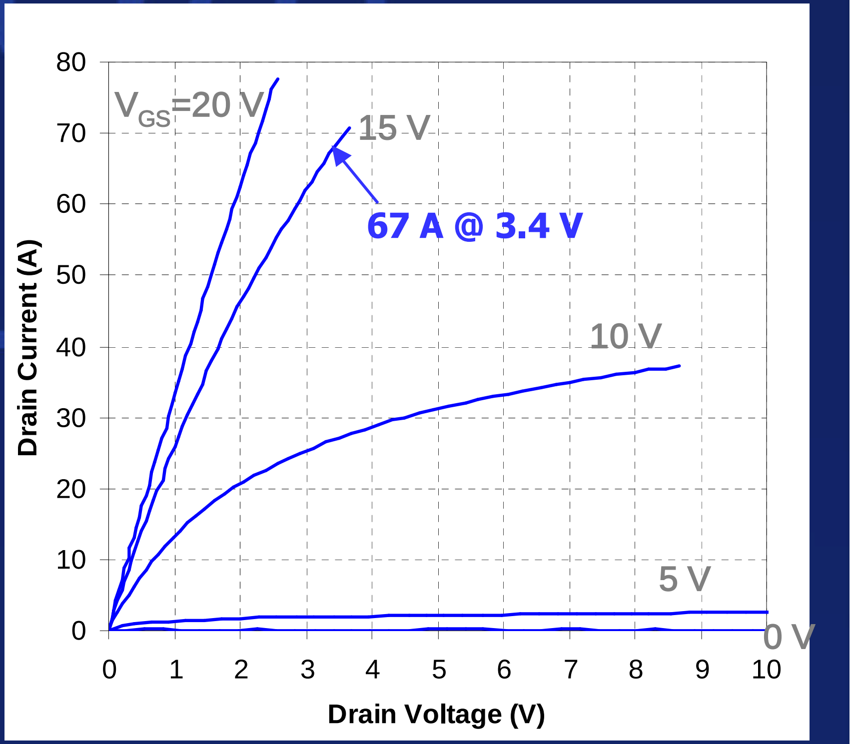
> 2x Reduction in Converter Losses + 150 °C Operating Temperature (Si = 125 °C)

> 4x Reduction in Cooling Requirements

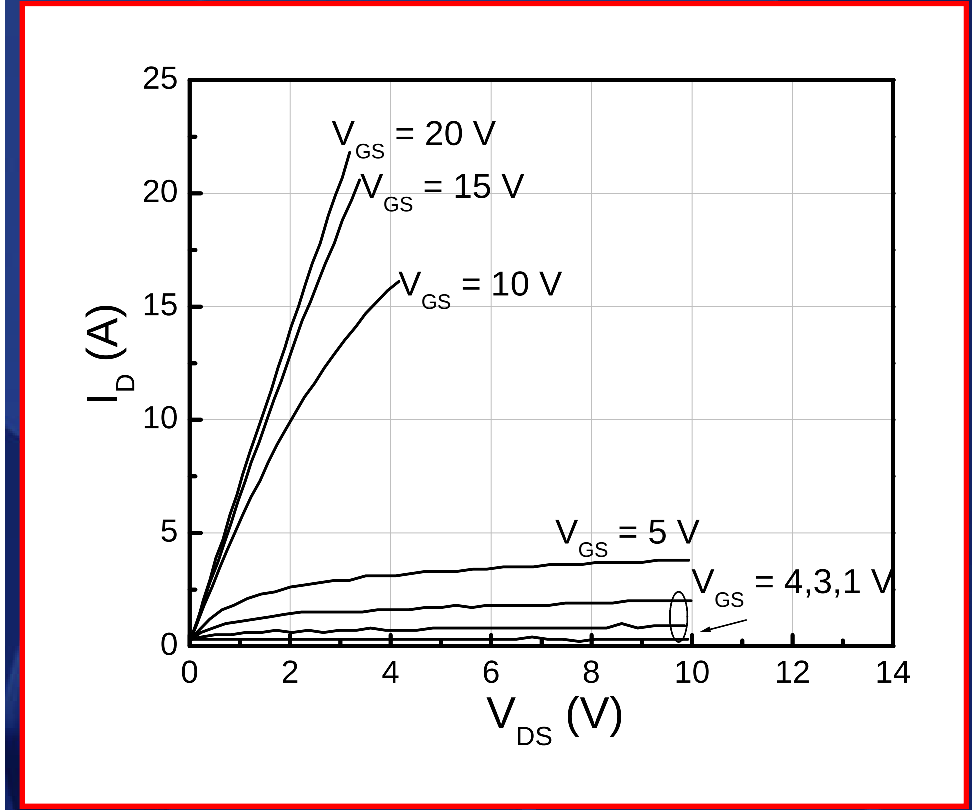
1.2kV/67A SiC DMOSFETs Fabricated on 3-Inch 4HN-SiC Wafer



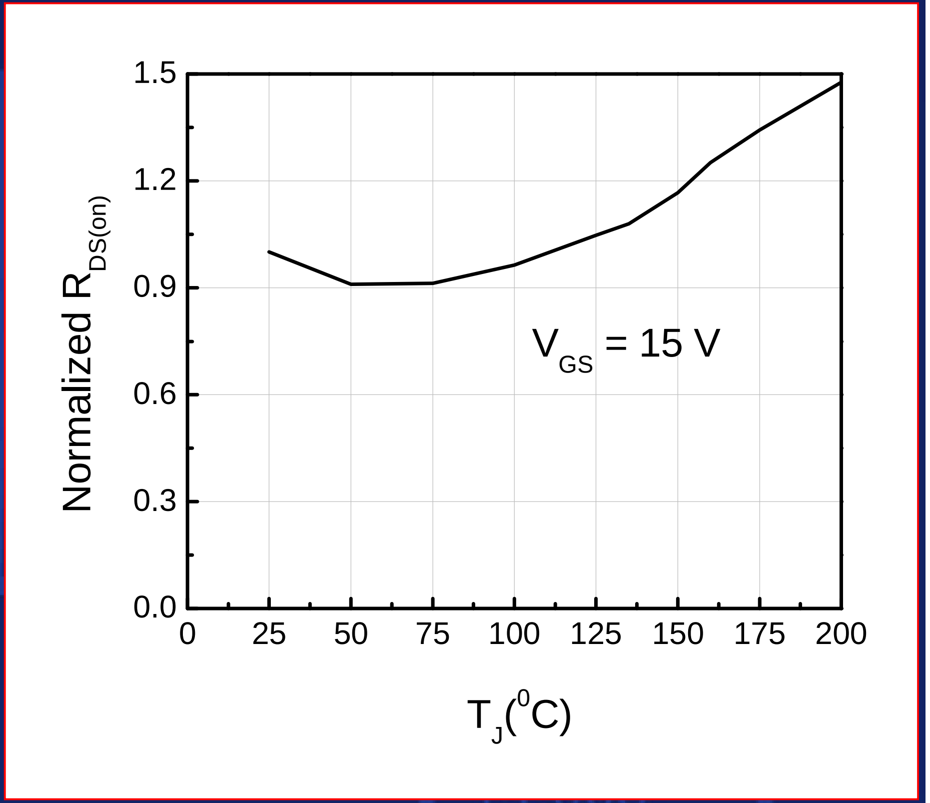




High Temperature Device Characteristics For 1.2kV/10A SiC DMOSFETs



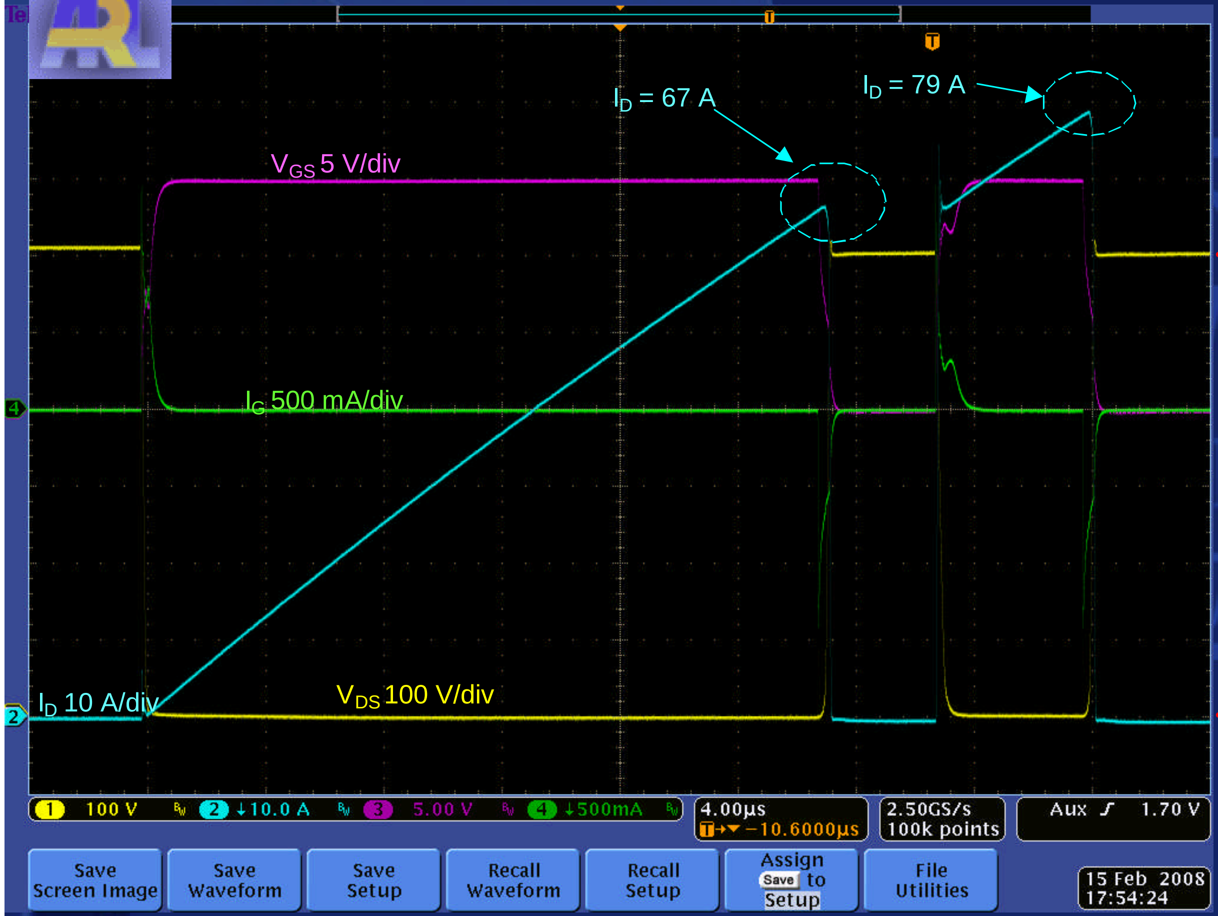
Typical Output Characteristics T_J = 150ºC

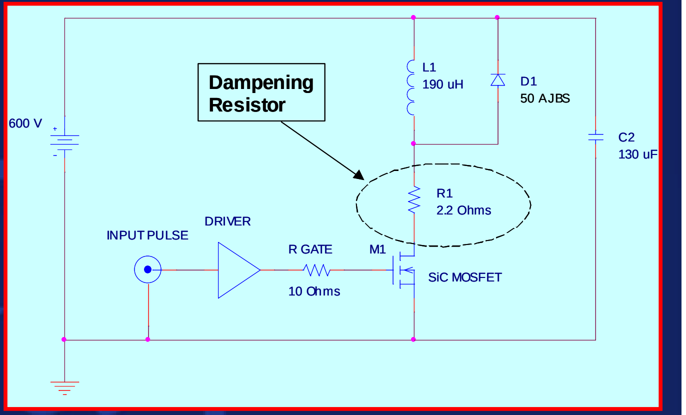


Normalized On-Resistance vs. Temperature

Creating Technology That Creates Solutions

1.2kV/67A SiC DMOSFET Switching Measurements at 150 °C

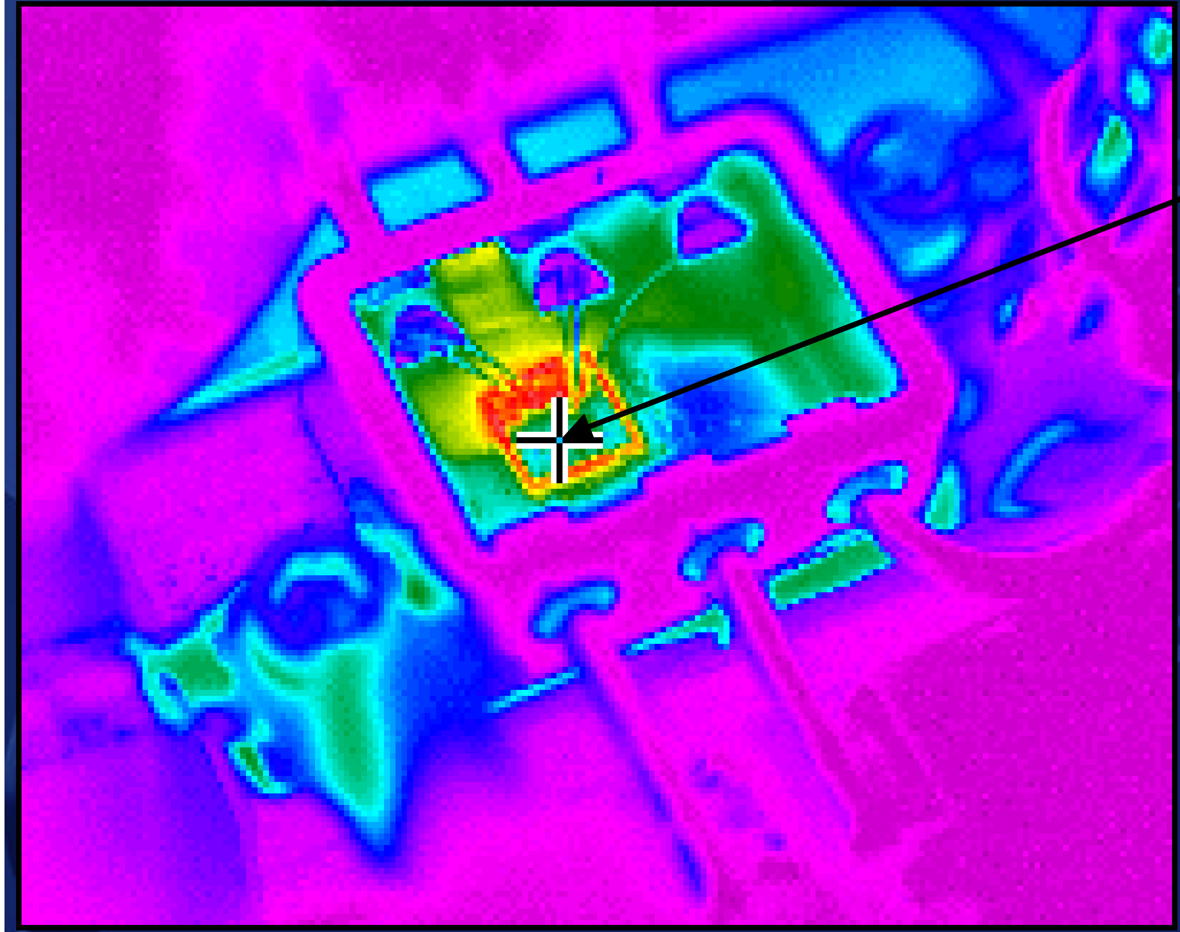




V_{DS} = 600 V

- **1.2kV/67A SiC DMOSFET Switching 67A at 150°C**
  - **E_{on} = 4.2 mJ**
  - **T_{rise} = 65 nsec**
  - **E_{off} = 3.1 mJ**
  - **T_{fall} = 68 nsec**

Boost Converter Demonstration of 1.2kV/10A SiC DMOSFET High Temperature Operation



- Thermograph Demonstrates 1.2kV/10A SiC DMOSFET High Temperature Operation (> 183 °C) Under Hard Switching Conditions
- 1.2kV/10A SiC DMOSFET Junction Temperature > 183 °C for 12 hrs
  - – No failures
  - – Stable operation

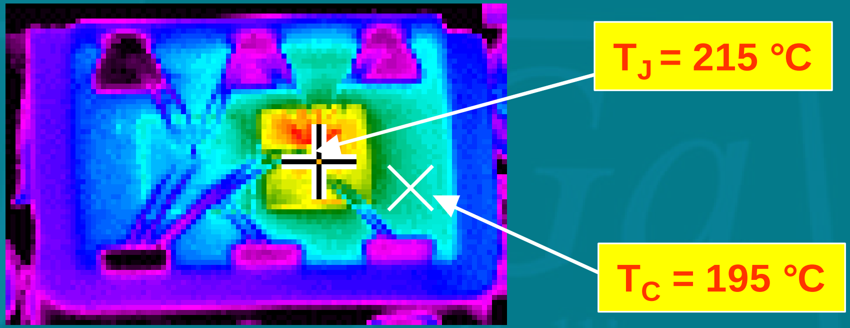
Excellent Current Sharing of Parallel 1.2kV/10A DMOSFETs in Boost Converter

Scale

227.2 °C

149.6°C

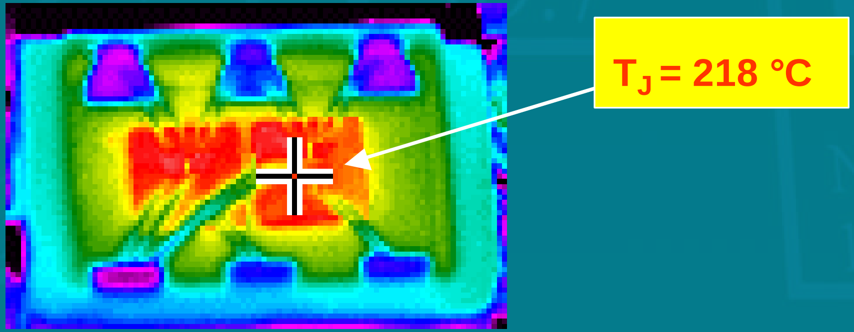
Single 1.2kV/10A SiC DMOSFET Operating @ 10.7 A RMS



T_J = 215 °C

T_C = 195 °C

2x Parallel 1.2kV/10A SiC DMOSFETs Operating @ 15.7 A RMS



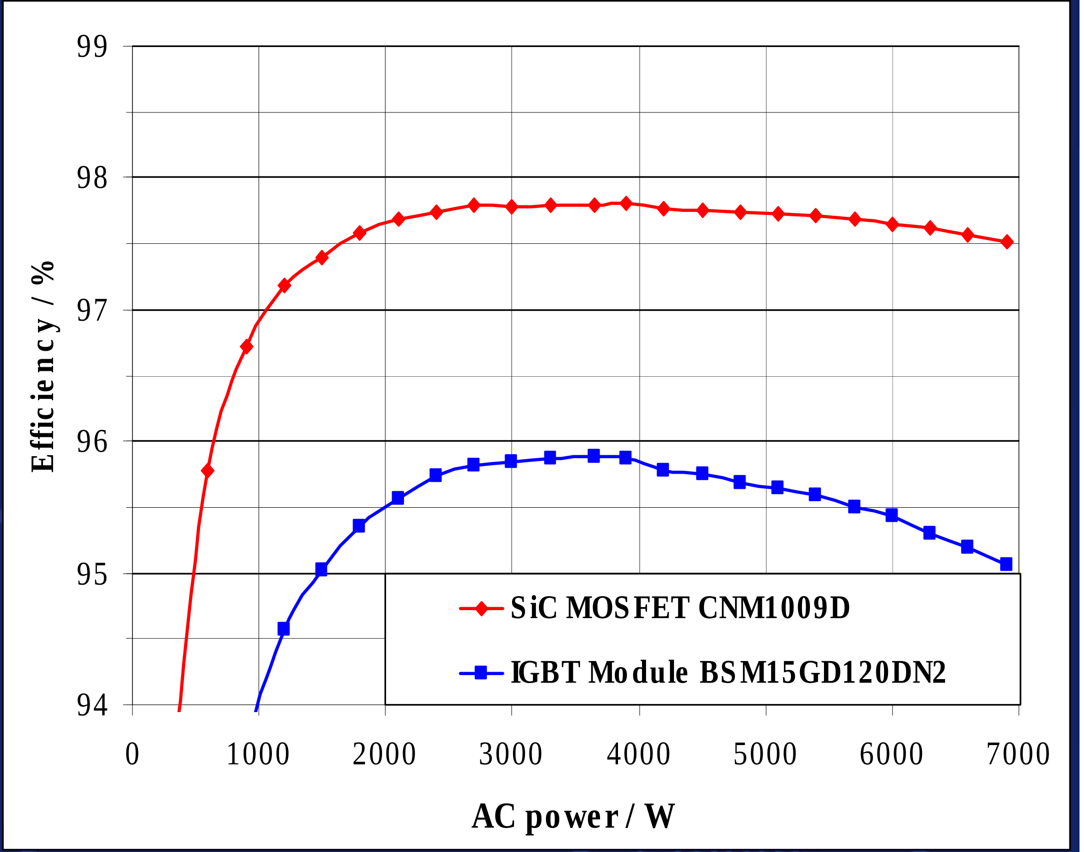
T_J = 218 °C

CREE

Creating Technology That Creates Solutions

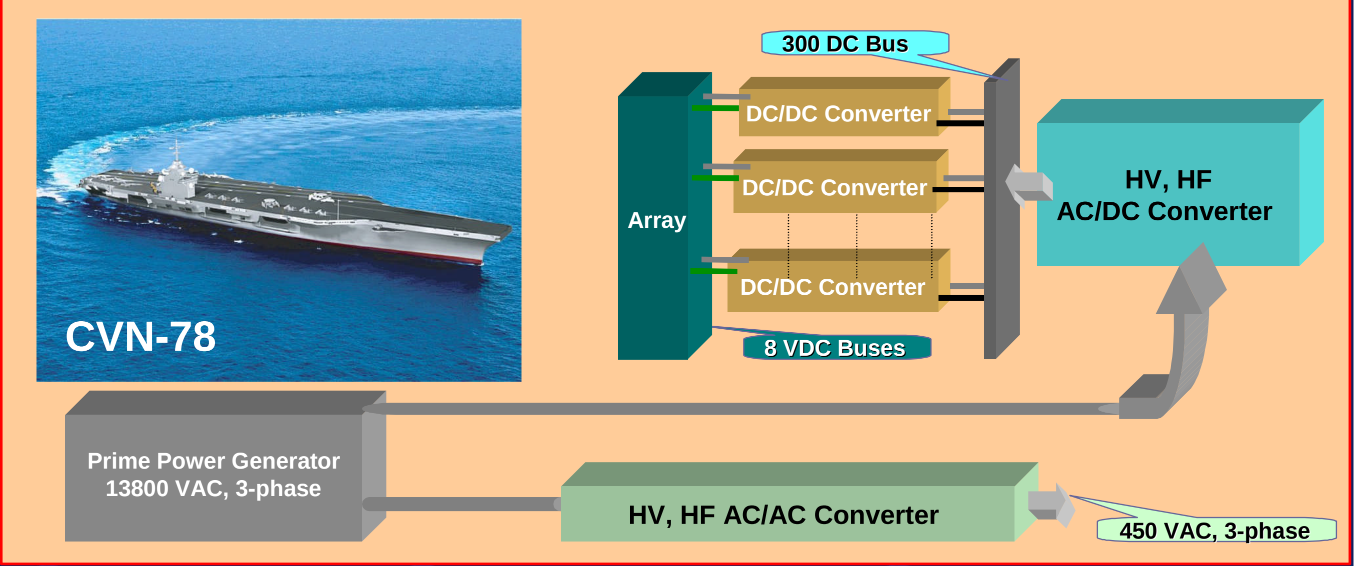
SiC 1.2 kV DMOSFETs Dramatically Improve Efficiency of 3-Phase 7kW Solar Inverter

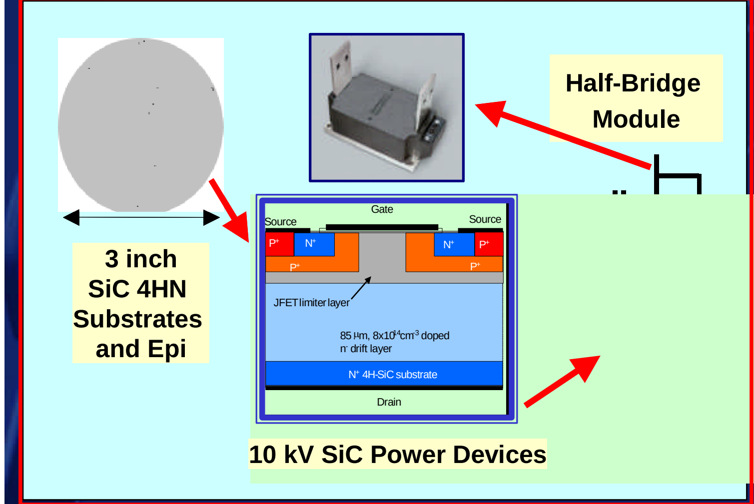
- Dr. Bruno Burger at Fraunhofer-Institute for Solar Energy Systems – 9/07
- Replaced Si IGBTs with 1.2kV SiC DMOSFETs In Existing Solar Inverter Without Further Optimization
- Efficiency Increased by 2.36%
- Huge Impact on Market - Typically Struggle for Tenths of a Percent Improvement



DARPA HPE
High Power SiC Module Development

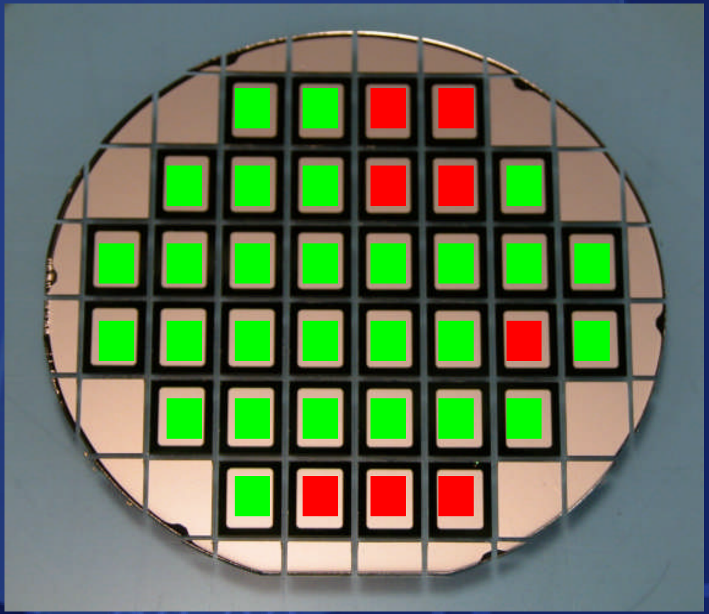
- **Develop SiC-Based Power Module for Solid State Power Substation (SSPS)**



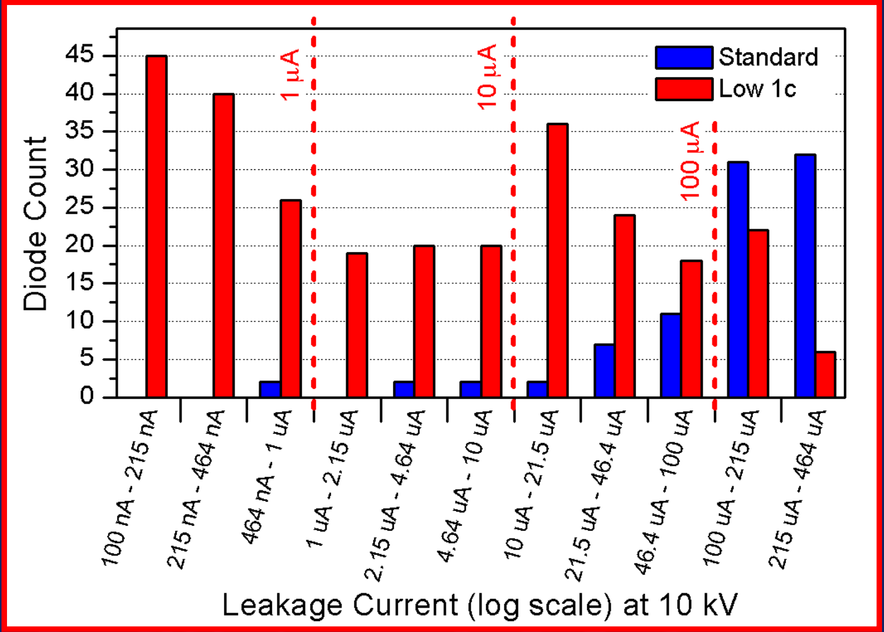


- **CVN-78 Power Distribution Uses 2.75 MVA/60HZ Power Transformers – Each Weighing Several Tons**
- **Develop SiC Power Module for Replacement SSPS 2.75 MVA 3-Phase Converter - 13.8kV AC to 465 AC**
- **Reduce System Weight by Factor of 10x**
- **Reduce System Size by Factor of 3x**
- **Demonstrate Comparable Efficiency ~ 97%**

High Yield Fabrication of 10kV/10A SiC JBS Diodes



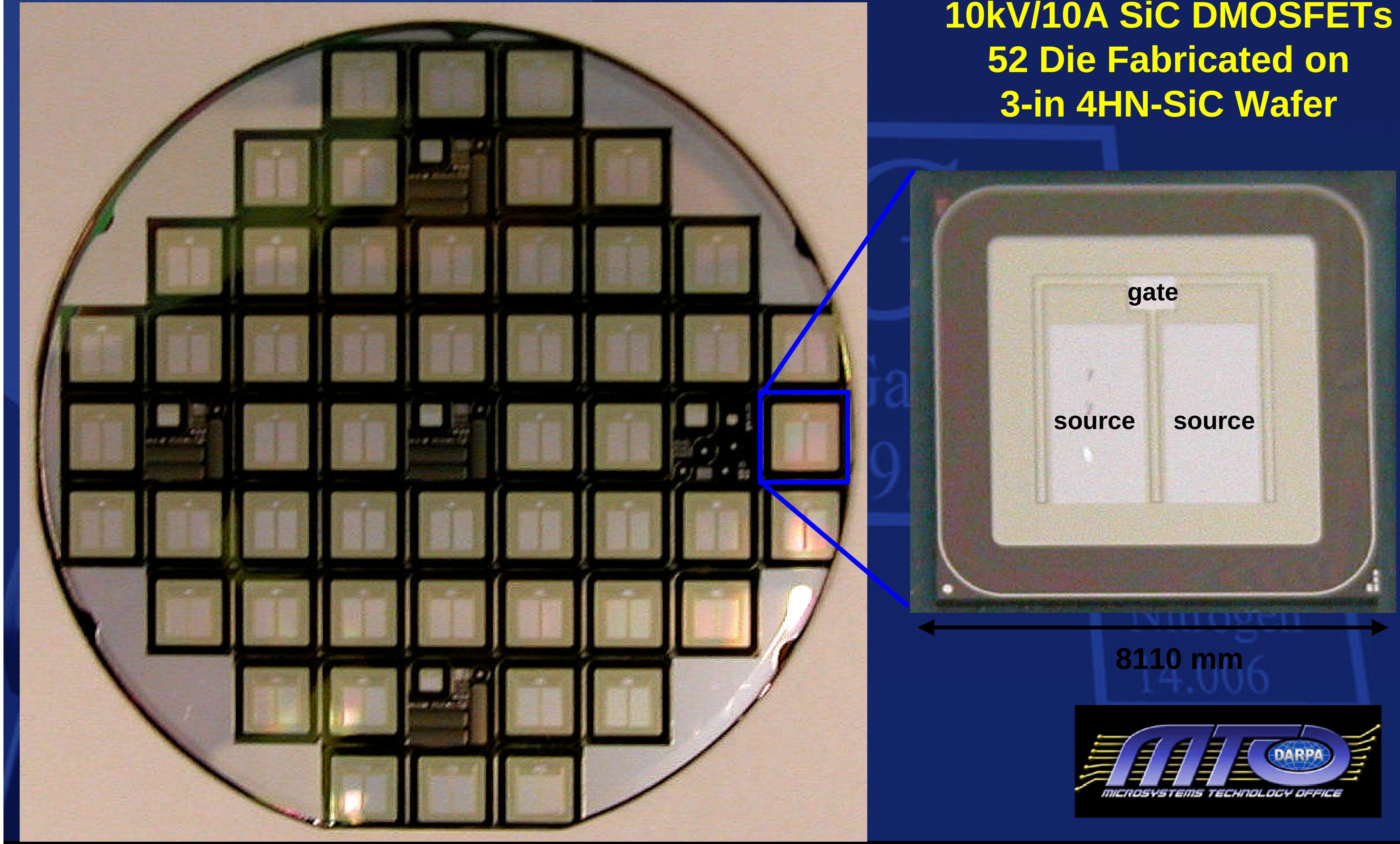
- **High Yield Fabrication of 10kV/10A SiC JBS Diodes on 3-inch Wafers**
  - **Highest Yield = 78%**
  - **Green $\Rightarrow$ Good Device on 3-inch Wafer**



Reverse Leakage Current Histogram of 10kV/10A SiC JBS Diodes

- **Low-1c SiC Wafers Dramatically Increase Yield of 10kV/10A SiC JBS Diodes**
  - **Median Reverse Leakage Current Decreased > 50X**
  - **Device Yield Increased > 3x**

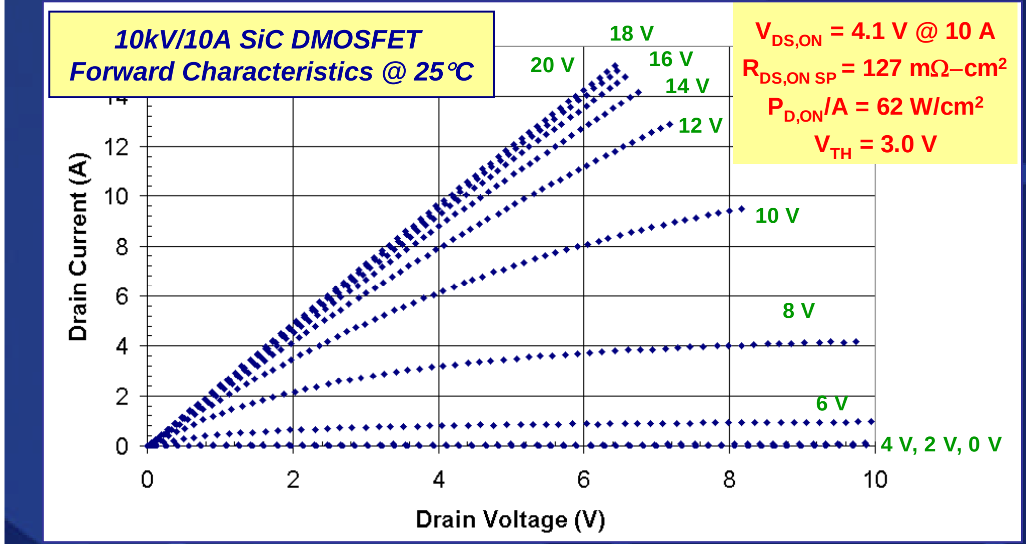
10kV/10A SiC DMOSFET



10kV/10A SiC DMOSFETs
52 Die Fabricated on
3-in 4HN-SiC Wafer

Creating Technology That Creates Solutions

High Yield Fabrication of 10kV/10A SiC DMOSFETs



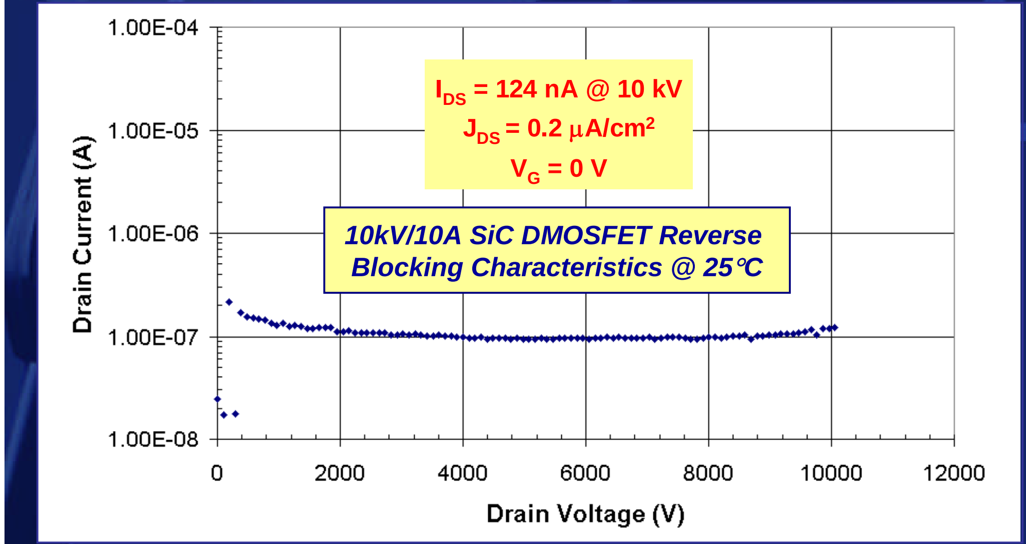
10kV/10A SiC DMOSFET Forward Characteristics @ 25°C

$V_{DS,ON}$ = 4.1 V @ 10 A

$R_{DS,ON\ SP}$ = 127 mΩ–cm²

$P_{D,ON}/A$ = 62 W/cm²

V_{TH} = 3.0 V

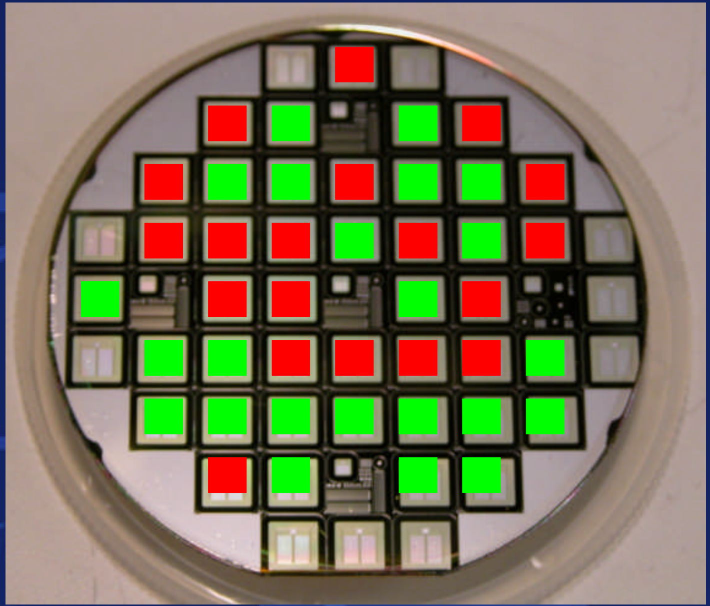


I_{DS} = 124 nA @ 10 kV

J_{DS} = 0.2 µA/cm²

V_G = 0 V

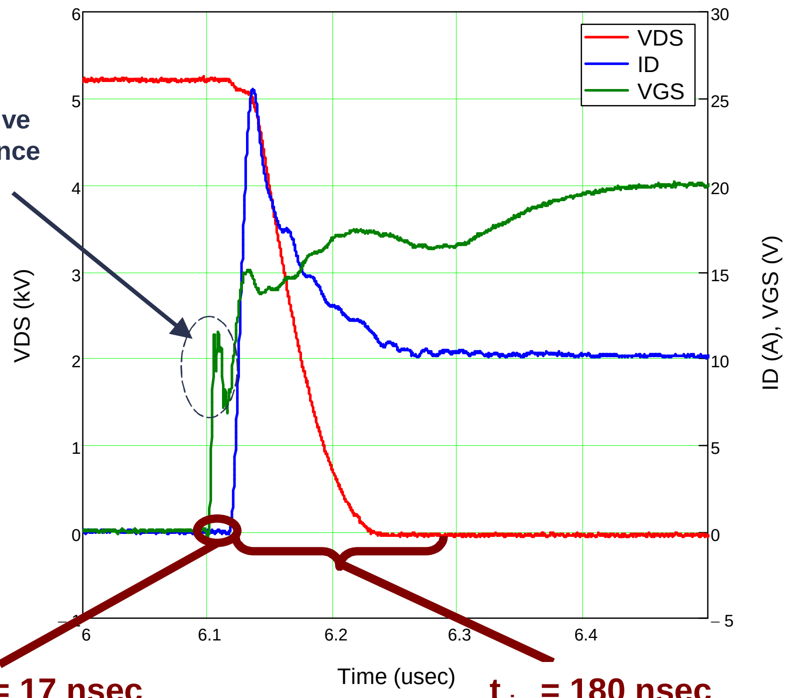
10kV/10A SiC DMOSFET Reverse Blocking Characteristics @ 25°C



- **High Yield Fabrication of 10kV/10A SiC DMOSFETs on 3-inch Wafers**
  - **Highest Yield = 55%**
  - **Green ⇒ Good Device on 3-inch Wafer**

10kV SiC DMOSFET/JBS Diode Clamped Inductive Switching

10 A Turn-On Gate Drive, V_{GS} = 20 V

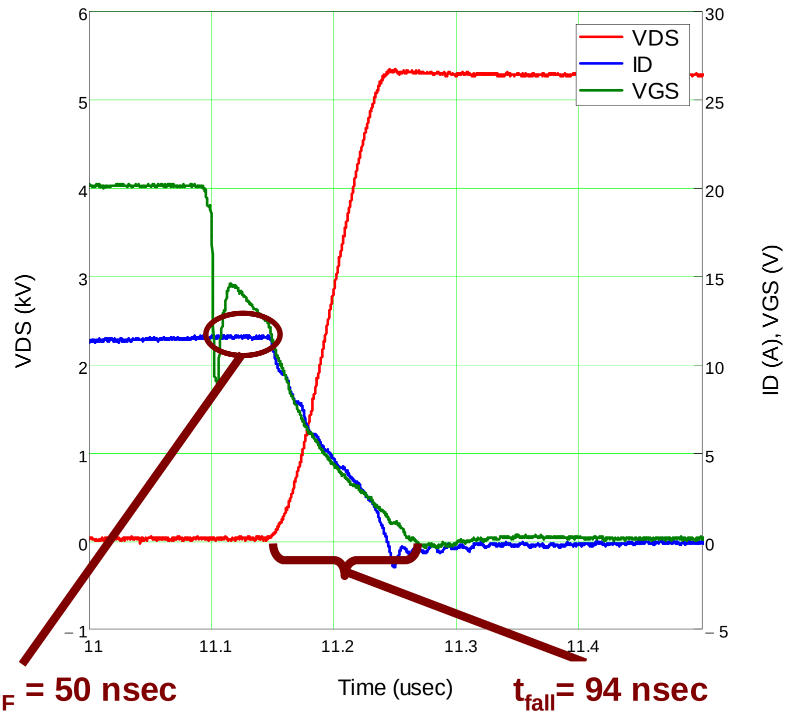


Gate drive inductance artifact

$t_{D,ON}$ = 17 nsec

t_{rise}= 180 nsec

10 A Turn-Off Gate Drive, V_{GS} = 20 V



$t_{D,OFF}$ = 50 nsec

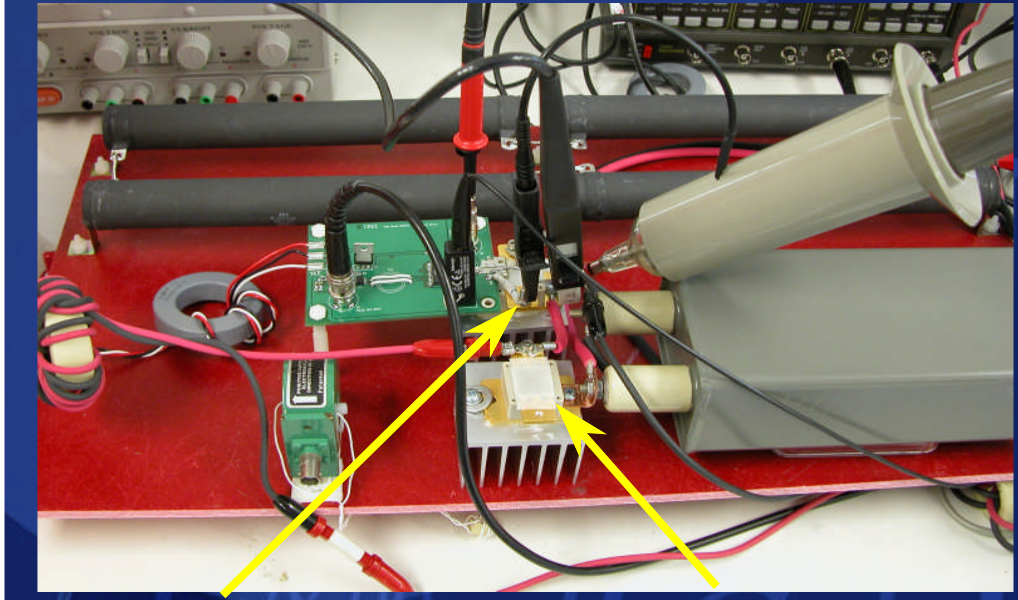
t_{fall}= 94 nsec

E_{on} = 4.48 mJ

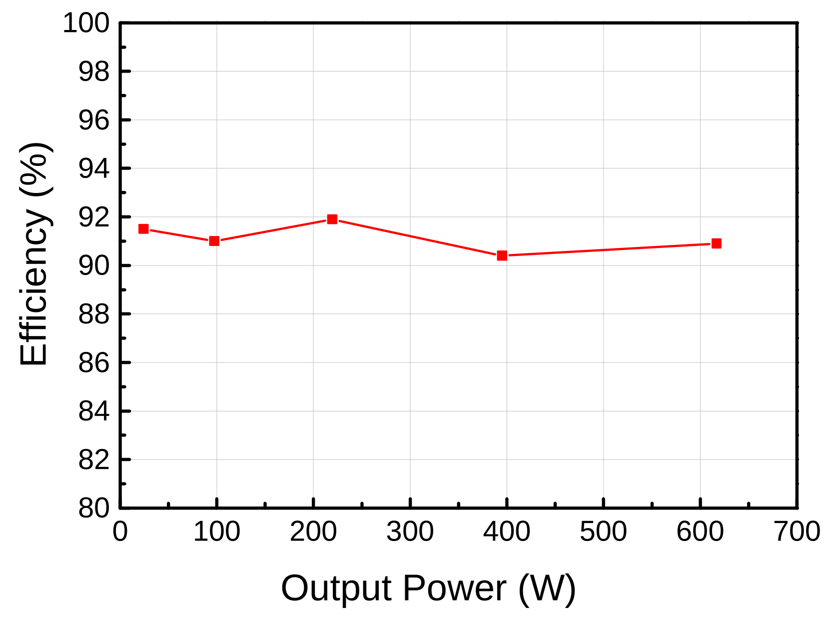
160 W/cm² Switching Losses Within Module Thermal Limits

E_{off} = 0.81 mJ

500V – 5kV / 20 KHz Boost Converter Using 10kV/10A SiC DMOSFETs and JBS Diodes

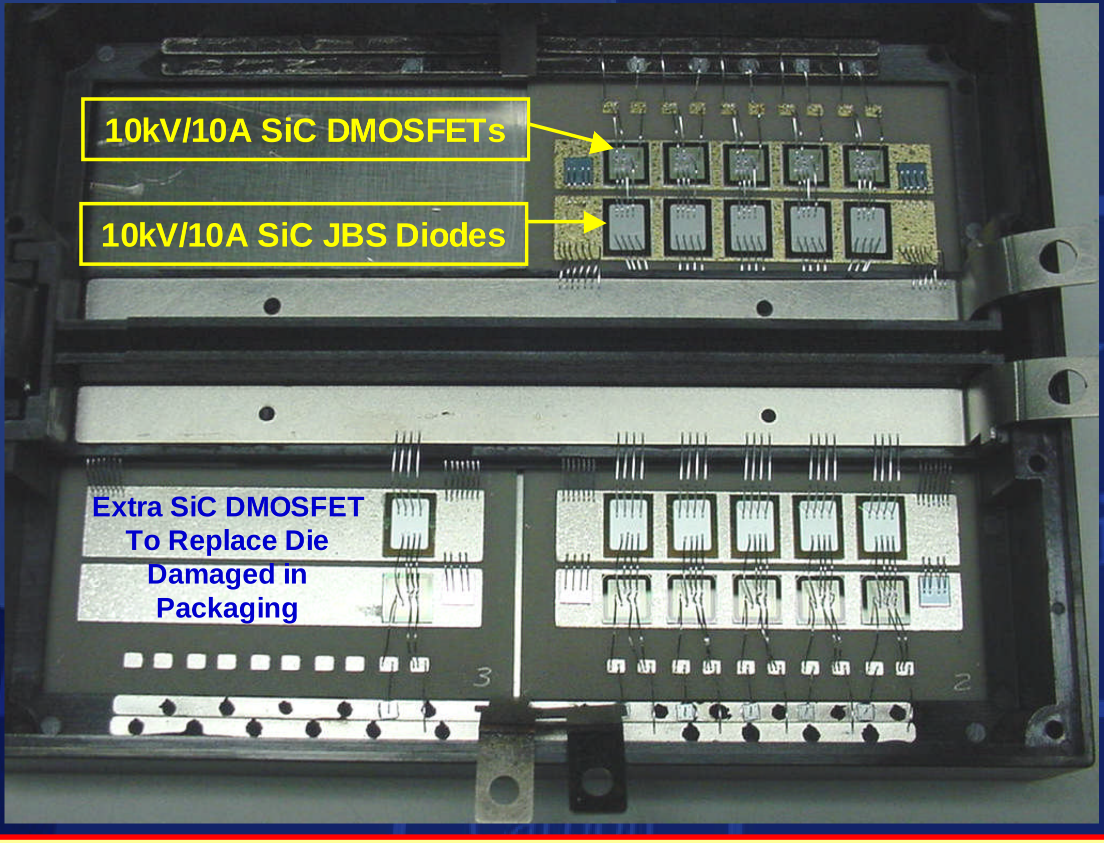


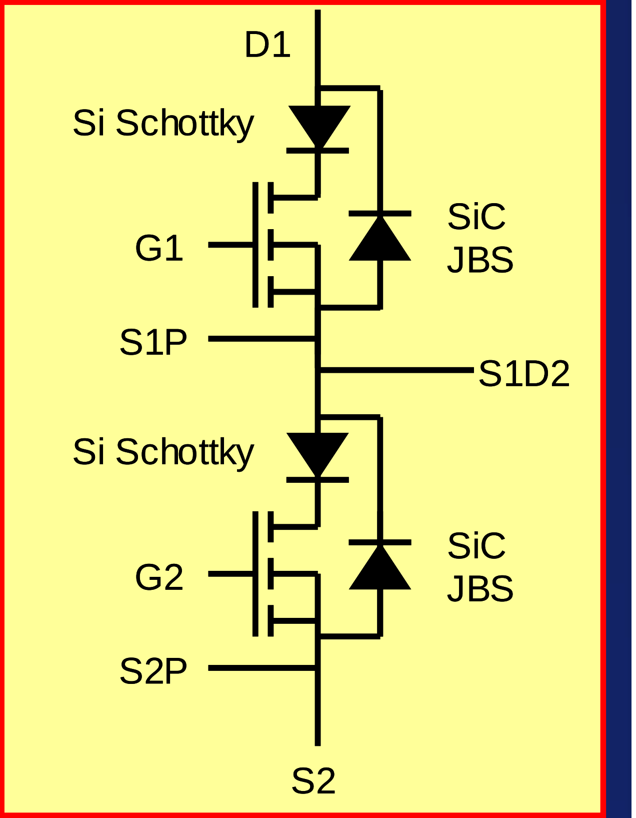
- **500V – 5kV Boost Converter Operating at 20kHz**
- **Maintained Efficiency > 90% Over Full Load Range**



Input	**Output**	**Duty Cycle**
V_{IN} = 503 V	V_{OUT} = 5 kV	90%
I_{IN} = 1.35 A	I_{OUT} = 0.12 A	Operating
P_{IN} = 679 W	P_{OUT} = 617 W	at 20kHz

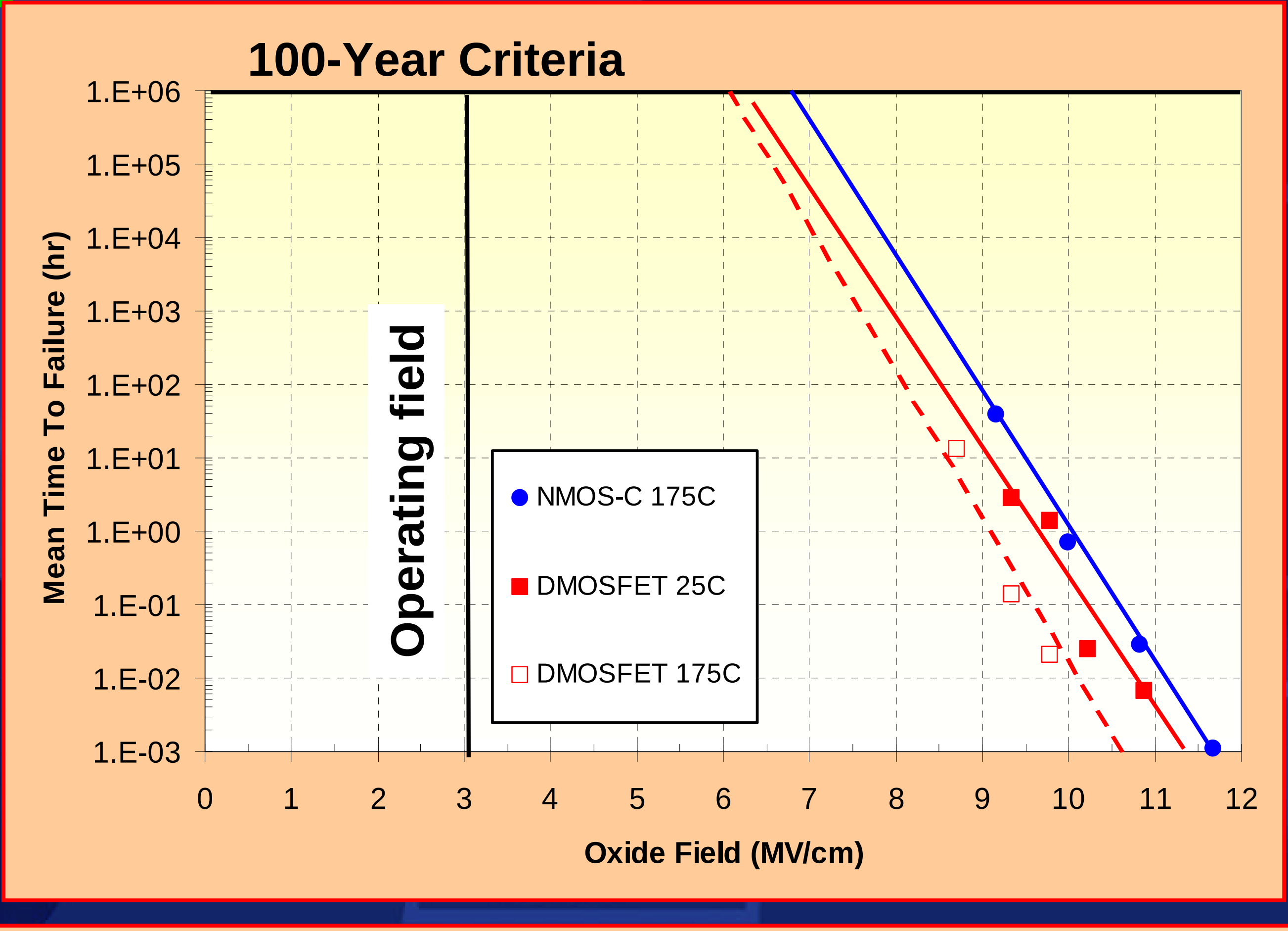
DARPA HPE-II 10kV/50A SiC Half H-Bridge Module





- Each Switch Comprised of 5 Paralleled 10kV/10A SiC DMOSFETs
- Each Rectifier Comprised of 5 Paralleled 10kV/10A JBS Diodes
- 10kV/50A Half H-Bridge Module Only Half Filled
- 10kV Half H-Bridge Module Capable of 100A When Fully Populated

TDDB Measurements of SiC DMOSFET Oxide Reliability



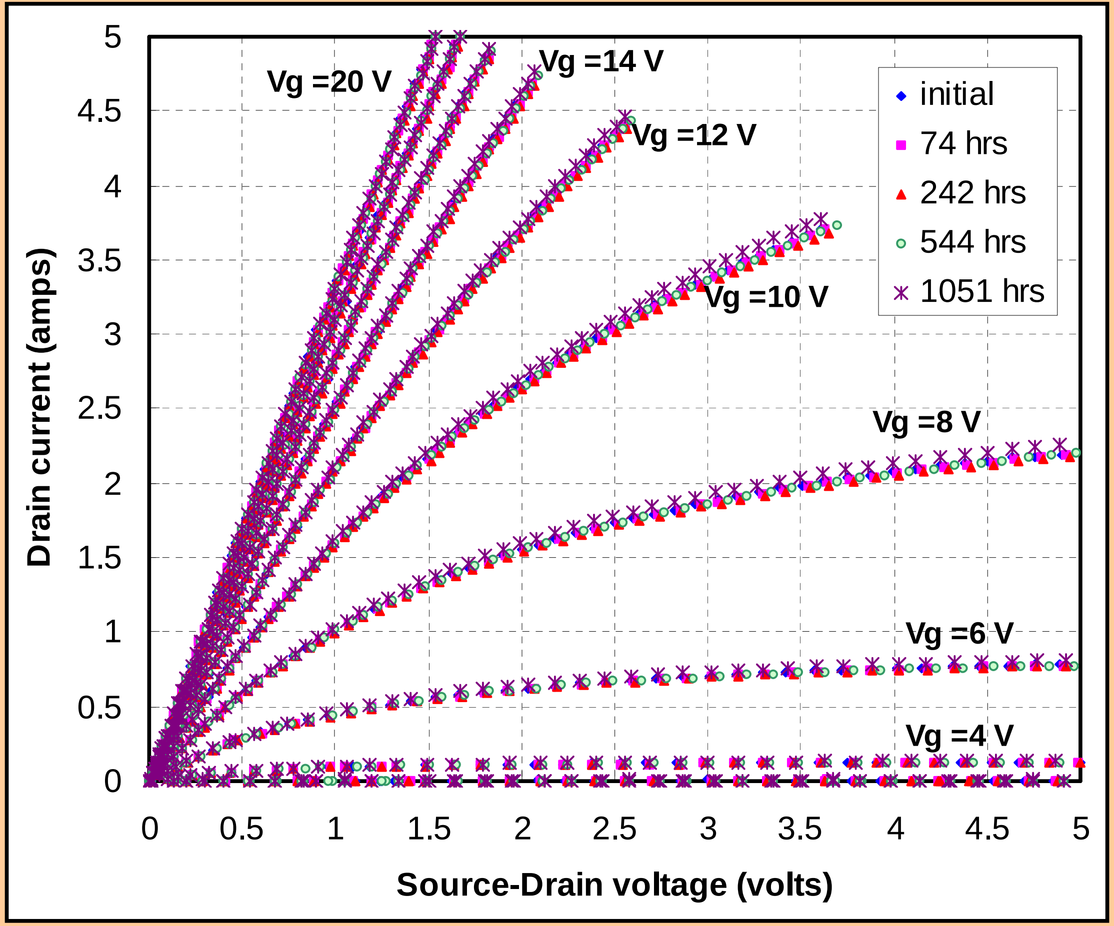
Measurements carried out on smaller DMOSFET devices fabricated without termination.

Device size: 4.9×10^{-4} cm^2

- **DMOSFETs show acceptable oxide lifetime at an operating field of ~3 MV/cm, despite ion implantation and high temperature annealing**

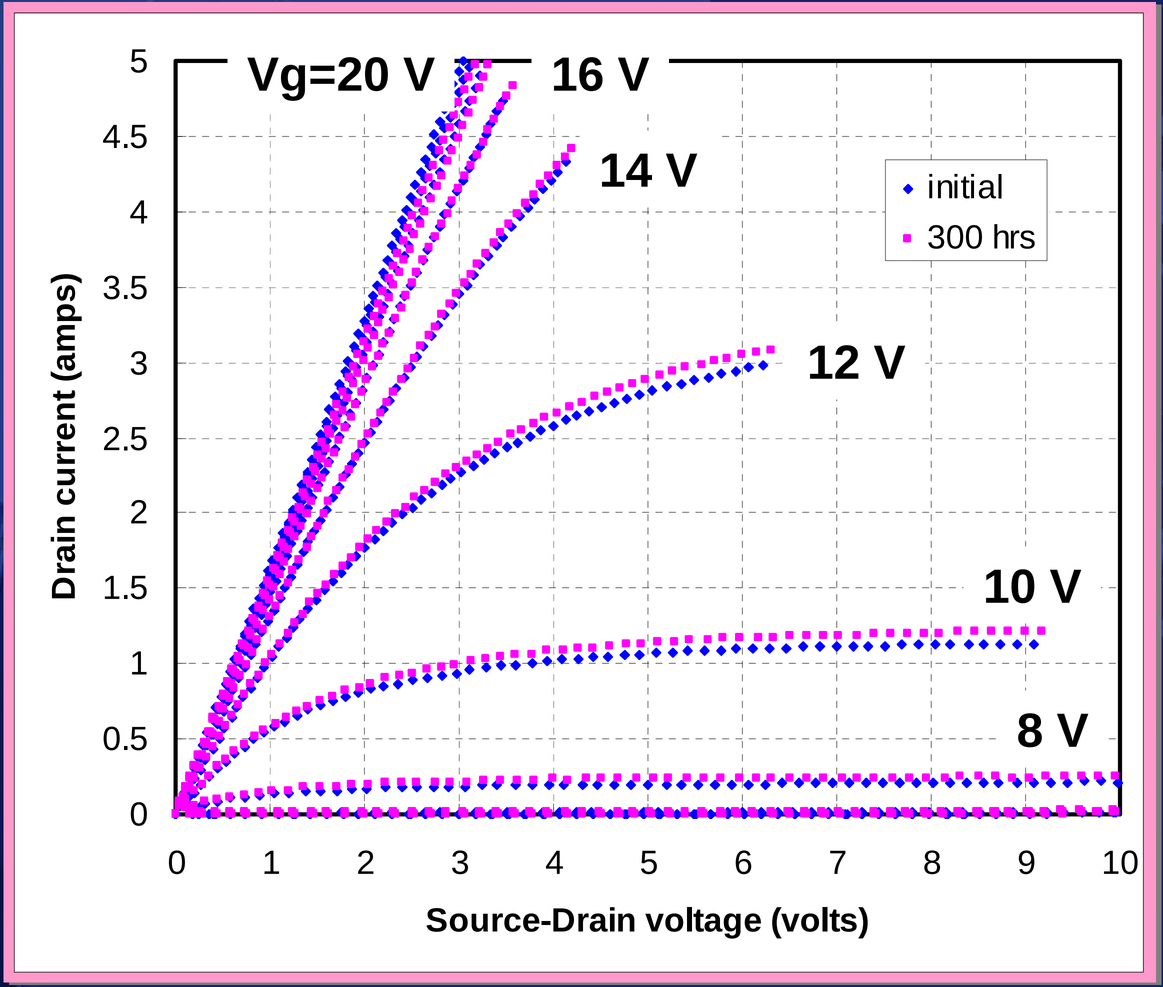
Stability of SiC 1200V/5A SiC DMOSFETs Under Constant Gate Stress at 175°C

5 A parts – Device size: 0.0753 cm^2



- Packaged SiC DMOSFETs Stressed at 175°C for Constant V_g = 15 V With Source & Drain Grounded
- Devices Cooled to RT and remeasured
- SiC DMOSFET I-V Curve Remains Relatively Unchanged After 1050 hrs of Stress

10 kV / 5 A 4H-SiC DMOSFET High Temperature Gate Stressing



- Packaged DMOSFETs stressed with V_g = 15V at 175°C, with source and drain grounded
- Devices cooled to RT and measured
- I-V curve remains unchanged after about 300 hrs of stress

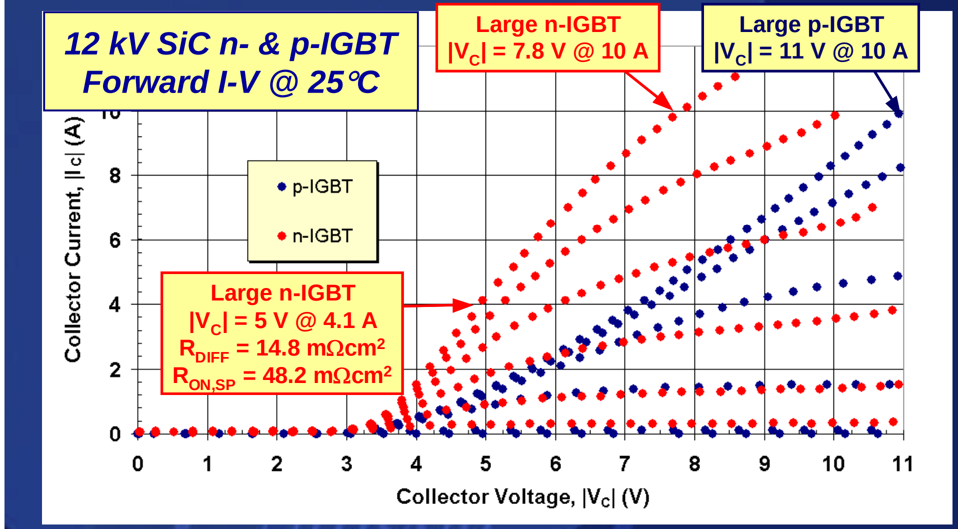
What Is Next for SiC Power Devices?

- **10 kV ~ Upper Limit of SiC Unipolar Devices**
  - **DMOSFETs and Schottky diodes**
- **Higher Voltage ⇒ Bipolar Devices**
  - **Si IGBT Replace Si DMOSFET at > 1kV**
- **For SiC devices, this holds true for >10 kV**
  - **SiC breakdown field 10x that of silicon**

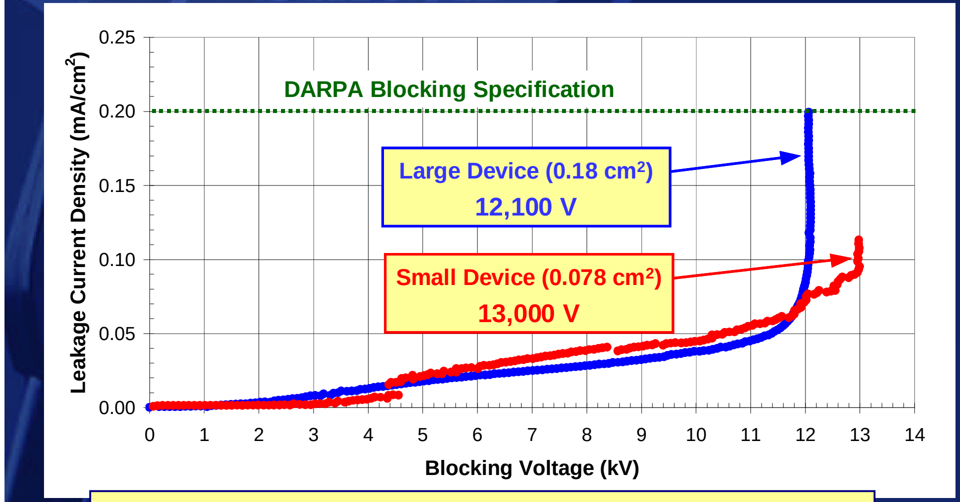
- **⇒ >10kV - We Need SiC IGBT**

12kV SiC n-IGBTs and SiC p-IGBTs

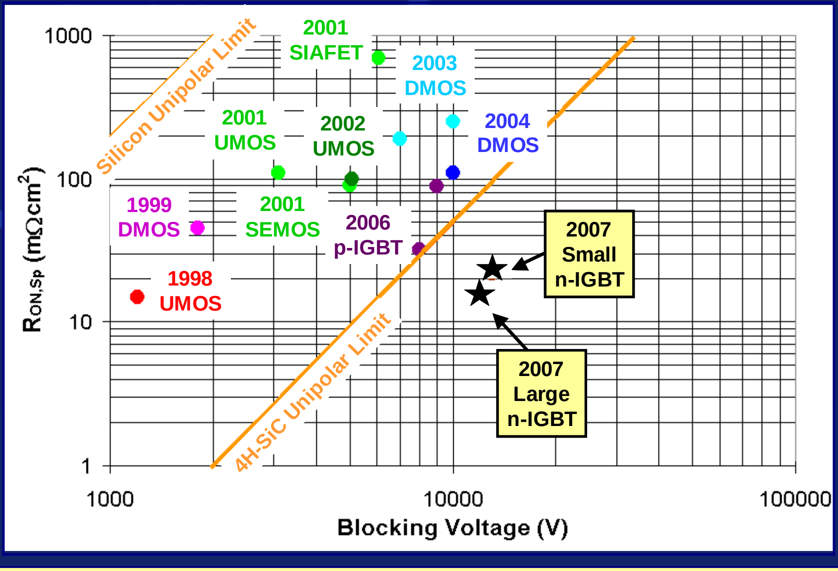
12 kV SiC n- & p-IGBT Forward I-V @ 25℃



- **12kV/10A SiC n-IGBTs and SiC p-IGBTs Demonstrated**
  - –SiC n-IGBTs Already Beyond $R_{on,sp}$/BV Limits for SiC DMOSFETs
  - –⇒ SiC IGBTs Superior to SiC DMOSFETs at BV > 10kV
  - –n-IGBT ~ n-type SiC drift layer p-IGBT ~ p-type SiC drift layer



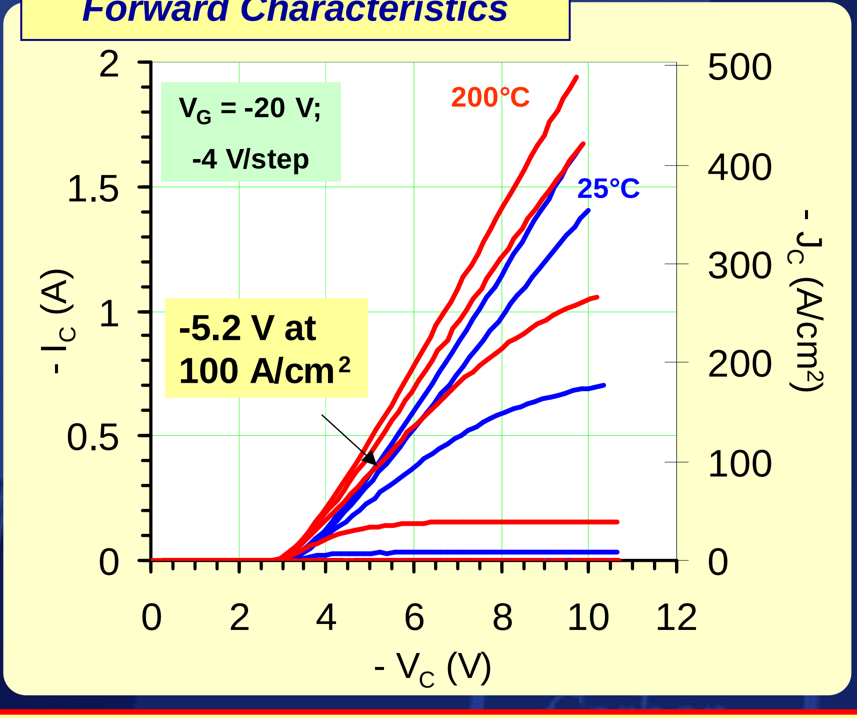
12 kV SiC n-IGBT Reverse Blocking @ 25℃

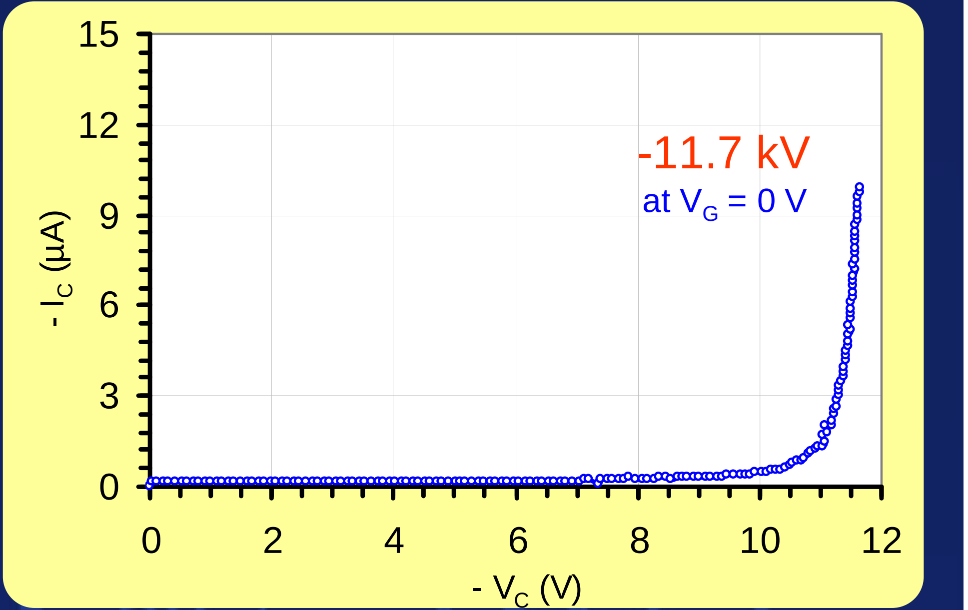


SiC n-IGBTs Beyond R_{on}/BV Limits for SiC DMOSFETs

12kV SiC p-IGBTs

12 kV SiC p-IGBT
Forward Characteristics



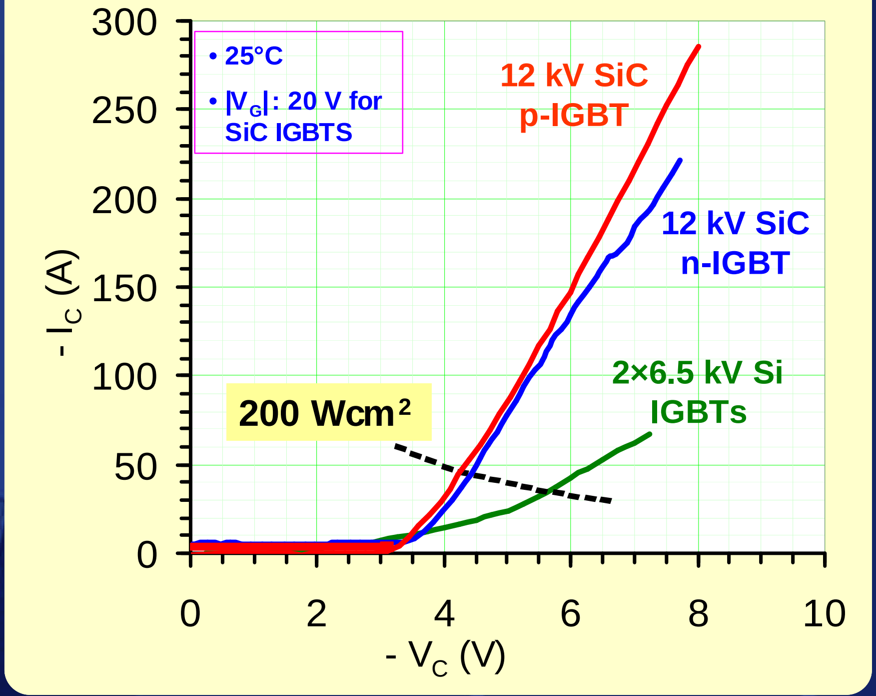


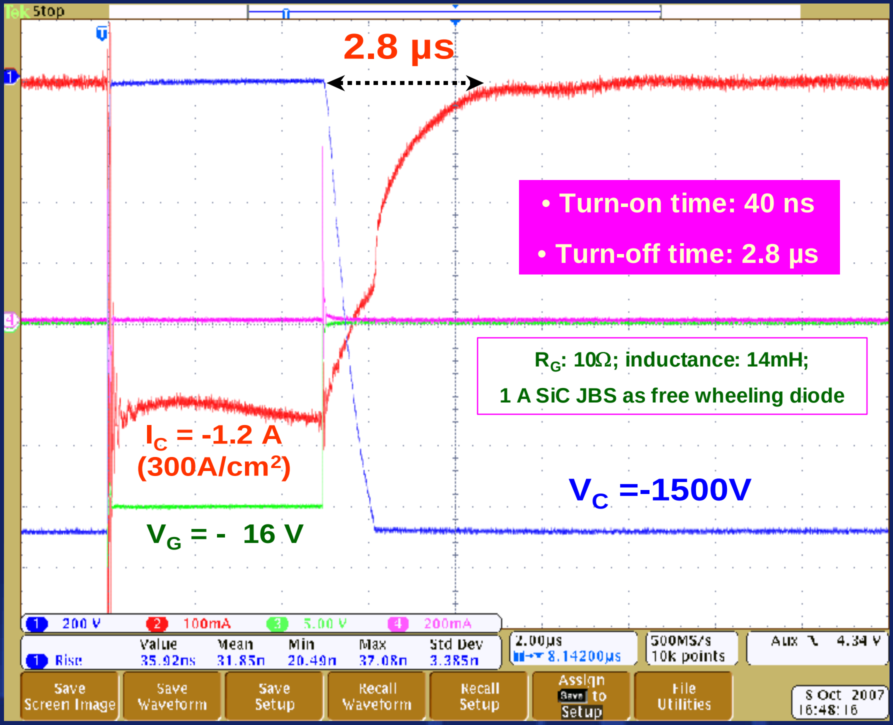
12 kV SiC p-IGBT Reverse
Blocking Characteristics @ 25°C

- 12kV SiC p-IGBTs Demonstrated From 25°C to 200°C
  - 12kV SiC p-IGBT V_f and Current Maintained From 25°C to 200°C
  - ⇒ Reduced Conduction Losses from 25°C up to 200°C
- SiC IGBTs Offer Advantages over SiC DMOSFETs at Blocking Voltages > 10kV

Comparison 12kV SiC p-IGBTs and Si IGBTs

12 kV SiC n-IGBT & p-IGBT Forward Characteristics





- Turn-on time: 40 ns
- Turn-off time: 2.8 μs

R_G: 10Ω; inductance: 14mH;
1 A SiC JBS as free wheeling diode

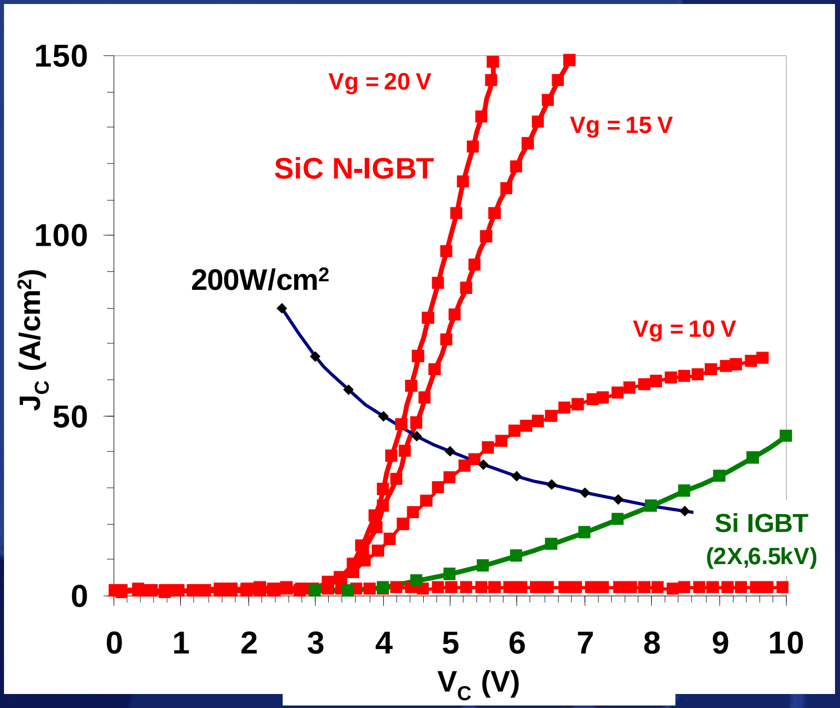
	Value	Mean	Min	Max	Std Dev
1 Rise	35.92ns	31.85n	20.49n	37.08n	3.385n

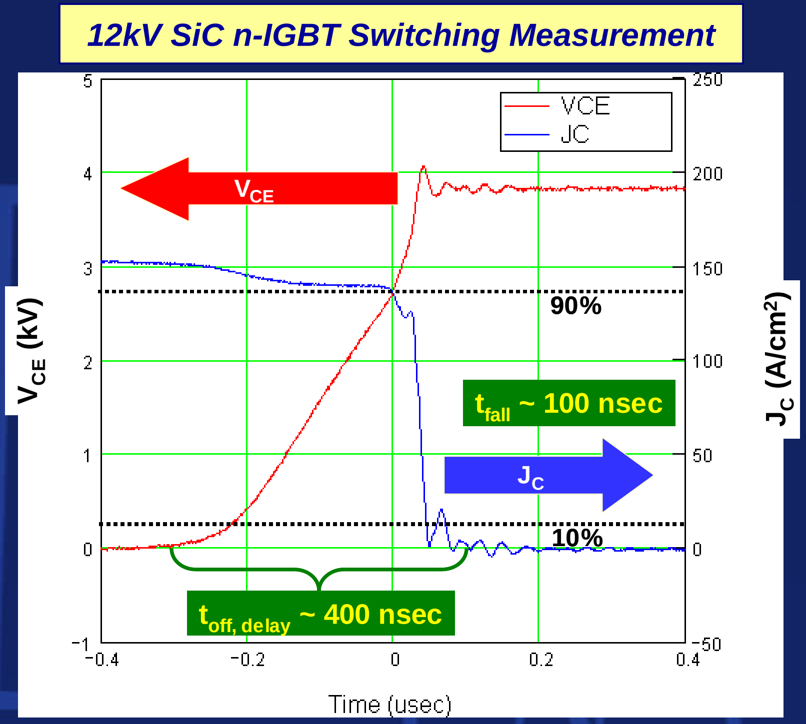
12kV SiC p-IGBT Switching Measurement

- **SiC IGBTs Are Superior to Si IGBTs at Higher Voltages**
  - **Much Lower Forward Voltage (V_F) & Higher Current Rating for Given Blocking Voltage**
  - **Dramatic Increase in Switching Speed – 12 kV SiC p-IGBT Turn-Off Time < 3 μs**

Creating Technology That Creates Solutions

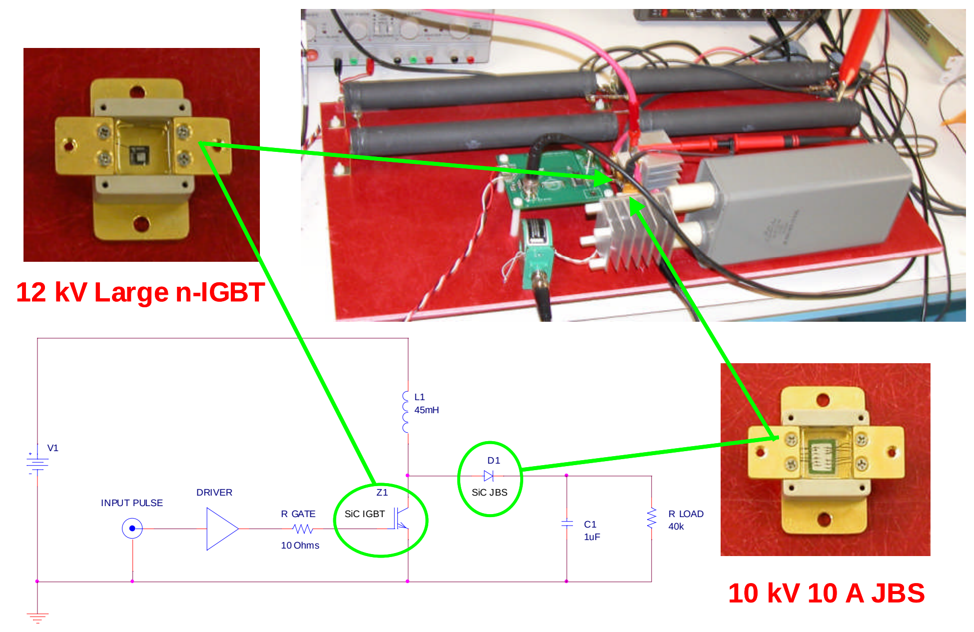
Comparison of SiC n-IGBTs and Si IGBTs





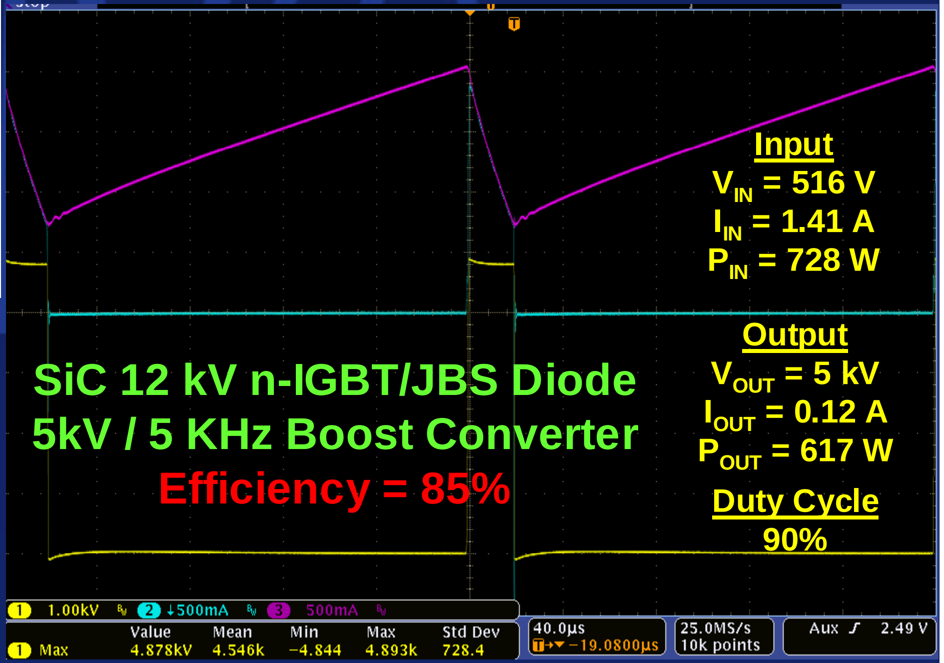
- **SiC IGBTs Are Superior to Si IGBTs at Higher Voltages**
  - –12kV SiC n-IGBTs Have >3x Lower $R_{on,sp}$ Than 6.5kV Si IGBTs
  - –SiC n-IGBTs Have Much Lower Forward Voltage (V_F) & Higher Current Than Si IGBTs at Same BV
  - –12kV SiC n-IGBTs Have 4x Faster Switching Speed and >4x Lower Switching Loss than 6.5kV Si IGBTs

12kV SiC n-IGBTs Boost Converter



- 12kV SiC n-IGBTs Used to Demonstrate 5kV/5KHz Boost Converter With 85% Efficiency

SiC n-IGBT/JBS Diode 5kV/5KHz Boost Converter



SiC 12 kV n-IGBT/JBS Diode
5kV / 5 KHz Boost Converter
Efficiency = 85%

Input
V_{IN} = 516 V
I_{IN} = 1.41 A
P_{IN} = 728 W

Output
V_{OUT} = 5 kV
I_{OUT} = 0.12 A
P_{OUT} = 617 W

Duty Cycle
90%

Its Time for SiC Power Technology!

"All I'm saying is <u>now </u>is the time to
develop technology to deflect the asteroid."

Creating Technologies That Create Solutions

Silicon Carbide
The Material Difference

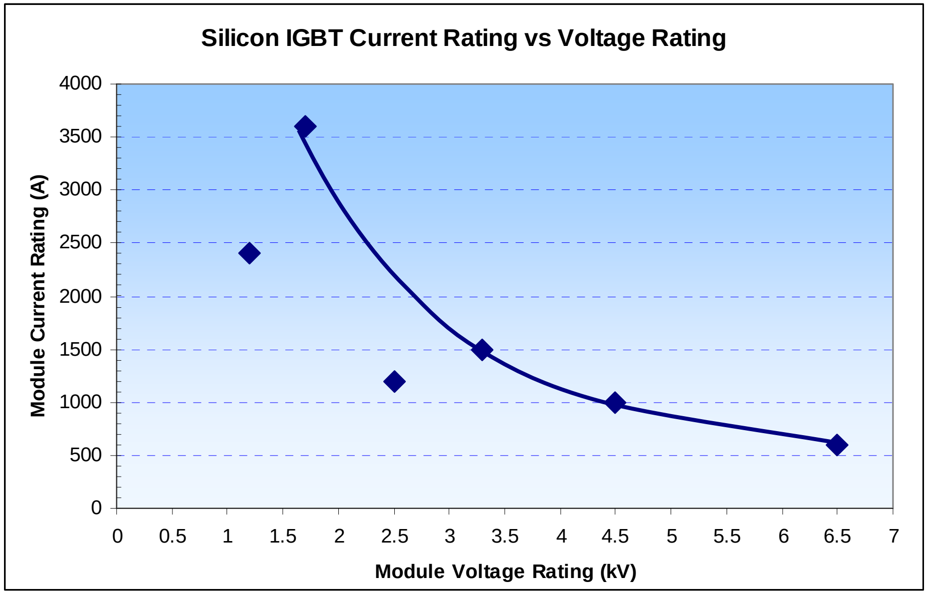
Advanced Power Modules & Packaging Technology

Scott Leslie
Chief Technologist

Advanced Power Module Technology - Outline

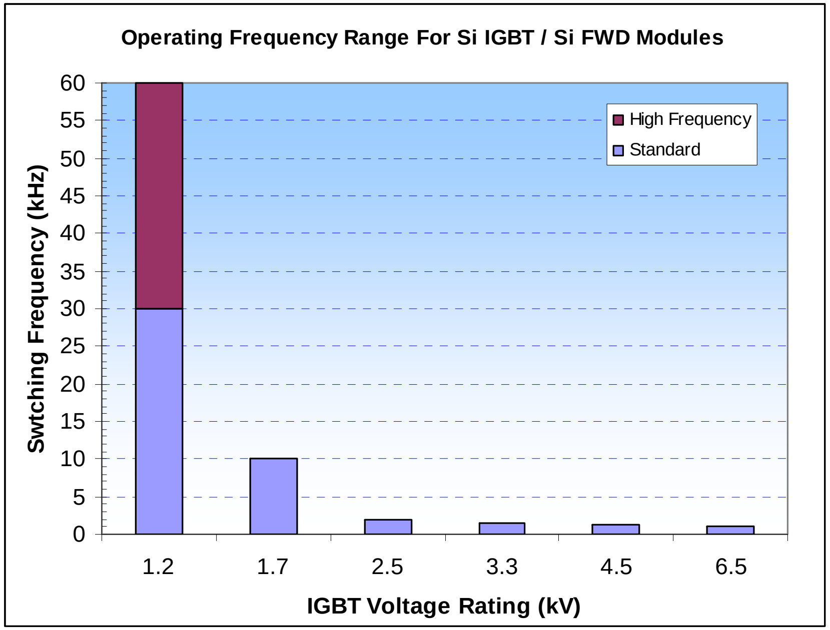
- Voltage & Frequency Limitations of Silicon Based Devices
  - Device Conduction & Switching Losses
- Alternatives to Silicon-Based Power Modules
  - Si IGBT / SiC FW Diode Hybrid Modules
  - All SiC Power Modules
- Technical Challenges for HV / HF Modules
  - Voltage Strike & Creep
  - Dielectrics
  - Inductance
  - Cooling
- Commercial Challenges For SiC Based Power Modules

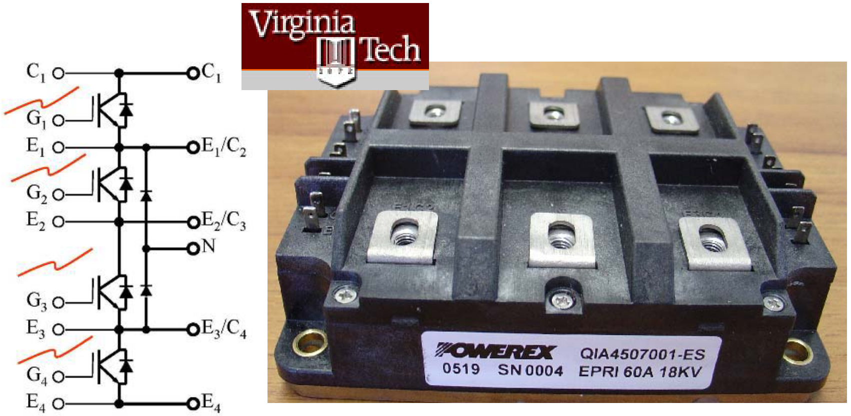
Present IGBT Module Ratings: 250V to 6.5kV



6.5 kV, 600A IGBT

Si IGBT Switching Frequency Capability Decreases Rapidly with Voltage Rating Due to Increased Losses



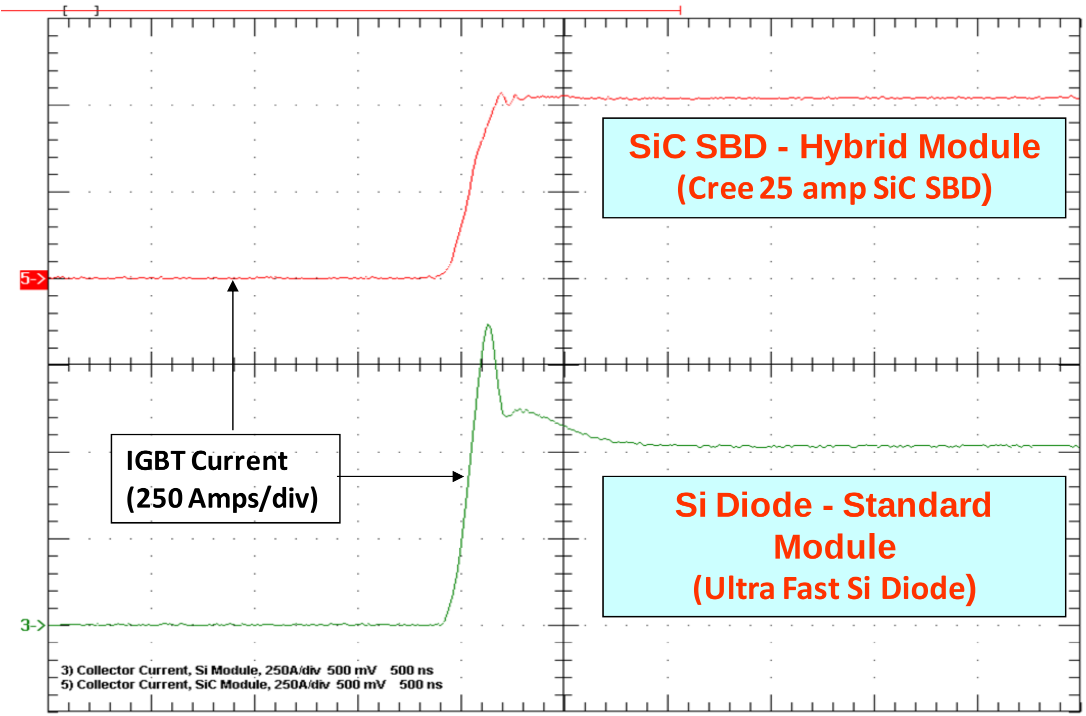


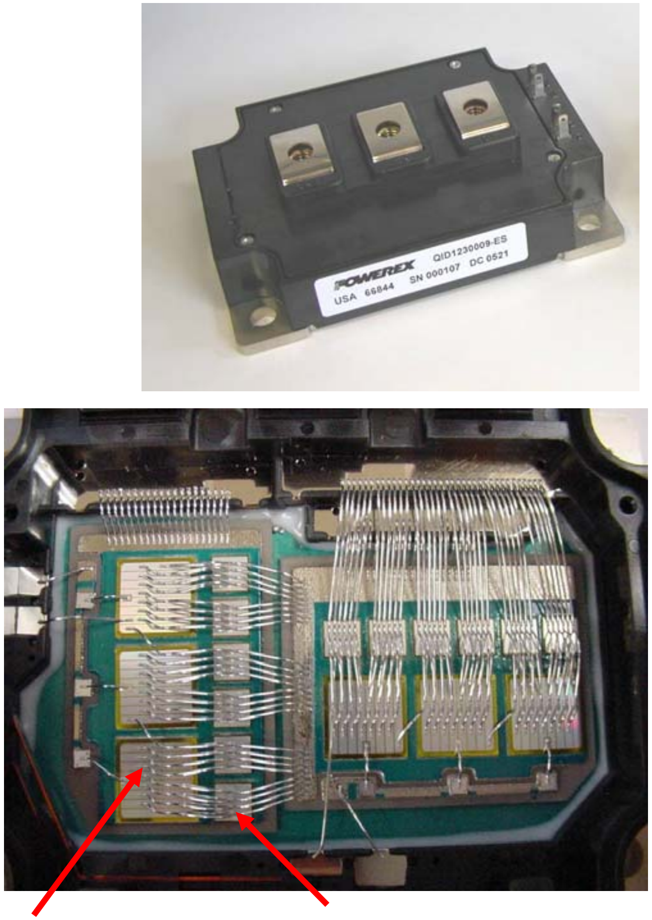
4.5 kV, 60A IGBT (3-Level diode-clamp)

Power Module Technology Trends

- Silicon Power Modules Rated to 6.5kV
  - Switching Frequency Limited for Modules Rated Above 1200V
  - Low Operating Frequency Does Not Permit Reduction of Passive Components
- Hybrid Silicon IGBT/SiC FW Diode Can Extend Switching Frequency
  - “Zero” Recovery Charge of HV SiC Schottky Diodes Reduce IGBT Switching Losses
- Shift to HV, HF SiC-Based Majority Carrier Switches
  - 1.2kV & 10kV SiC MOSFETs Developed
  - Higher Temperature Capability of SiC Can Lead to Higher Converter System Power Densities & Relaxed Cooling Requirements
  - Higher Frequency Reduces Passive Component Sizes

SiC Shottky FW Diodes Reduce Si IGBT Switching Losses

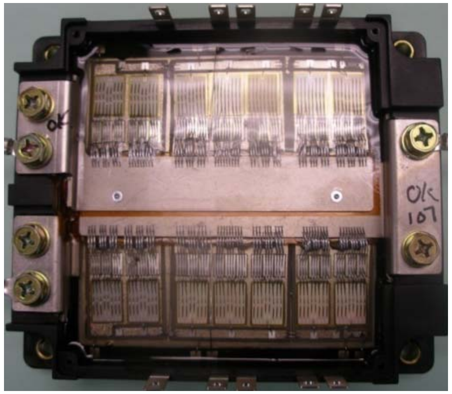


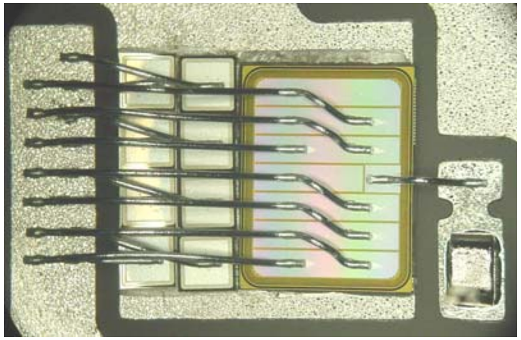


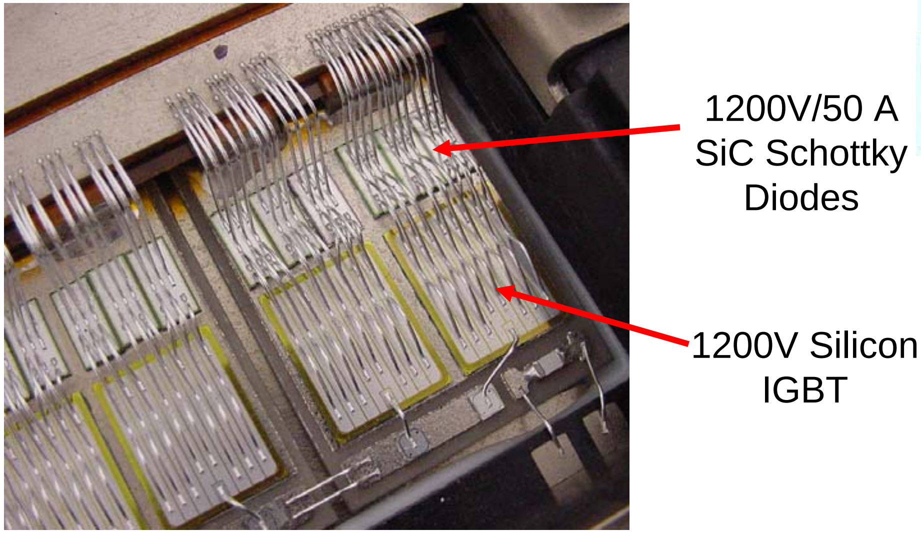
300A -1200V Dual Si/SiC Hybrid Module

1st Annual Ground -Automotive Power & Energy Symposium
July 20-22, 2005, Hilton, Detroit/Troy

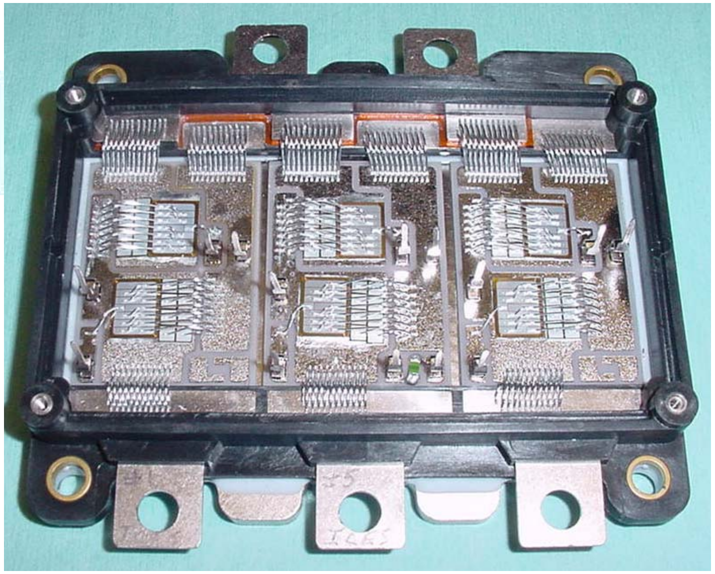
Si IGBT / SiC FW Diode Dual & 3 **F** Bridge Modules





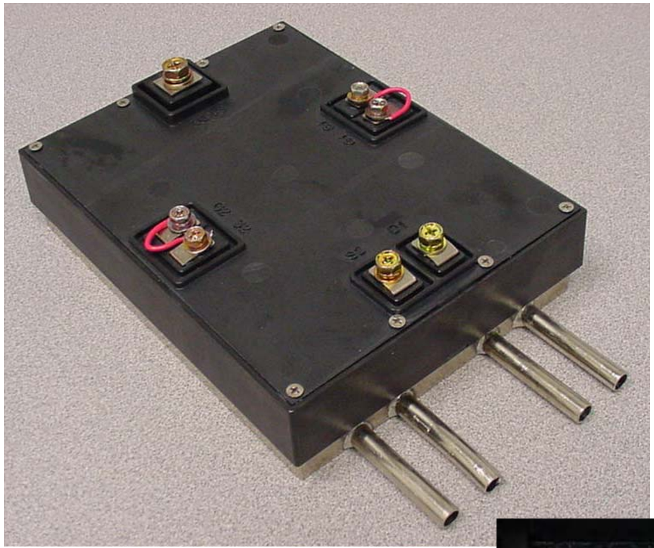


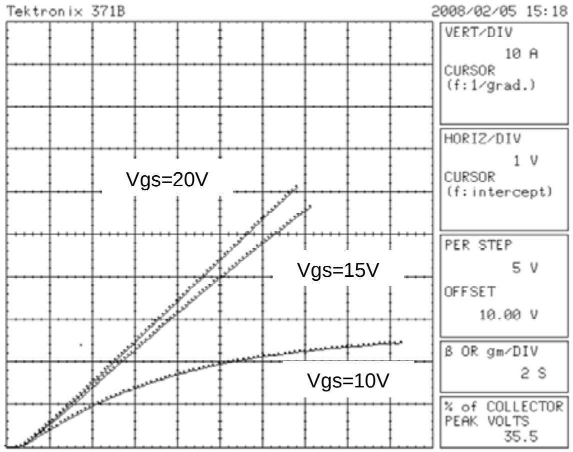
1200A -1200V Dual Si/SiC Hybrid Module



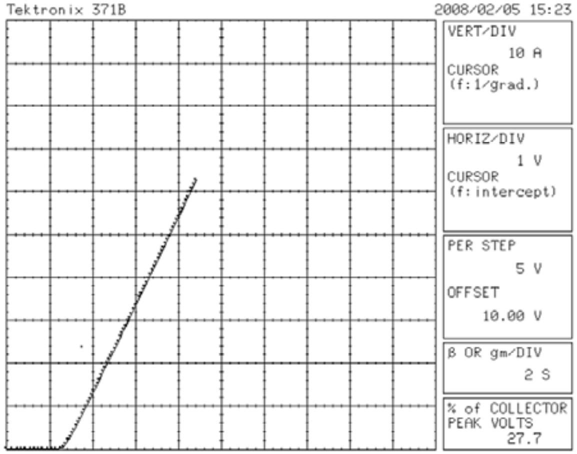
75A -1200V 3-**F** Si IGBT / SiC FW Diode Module

10kV, 50A SiC MOSFET/ SiC Schottky Half H-Bridge Module





Q1 MOSFET



Q1 JBS Diode

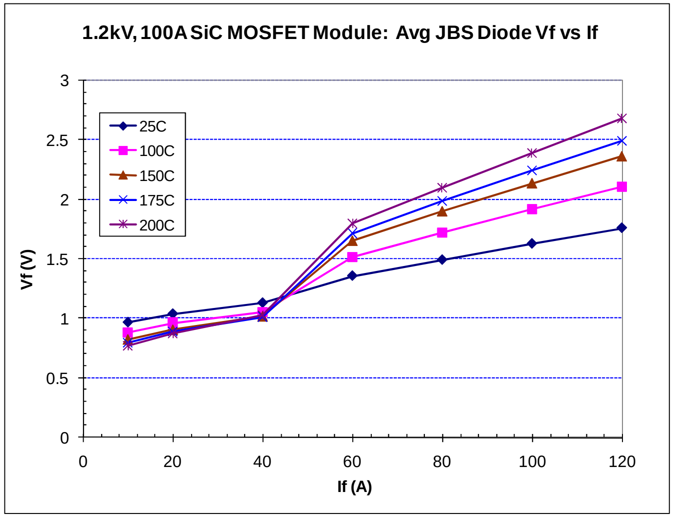
Test	Q1	Q2
Igs @ Vgs = 15V	2 uA	2 uA
Ids @ Vds = 3kV	0.6 uA	0.1 uA
Ids @ Vds = 5kV	2.6 uA	0.6 uA
Ids @ Vds = 6kV	5.1 uA	1.3 uA
Vds @ Ids = 50A Vgs = 15V	6.3 V	6.1 V
Vds @ Ids = 50A Vgs = 20V	5.6 V	5.5 V
JBS Diode Vf @ If = 50A	3.8 V	3.9 V

All Tests @ 25C

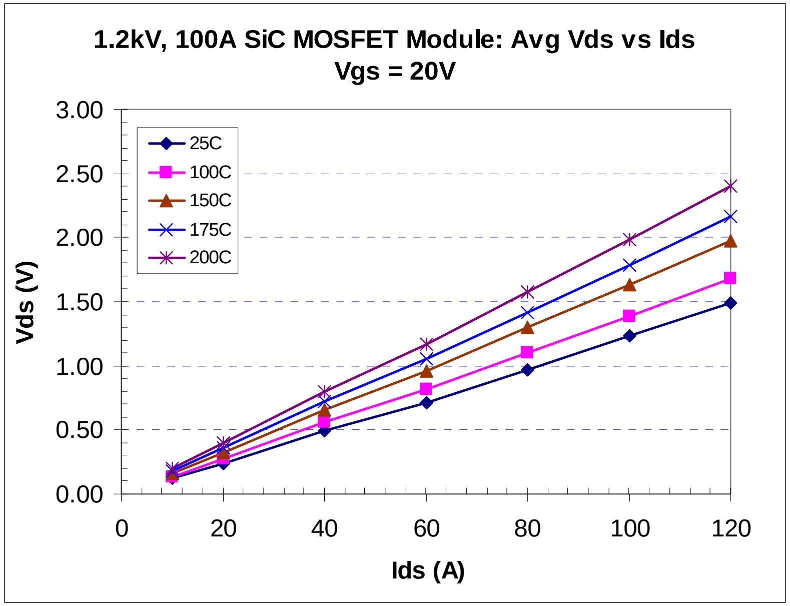
HPE Phase II Module

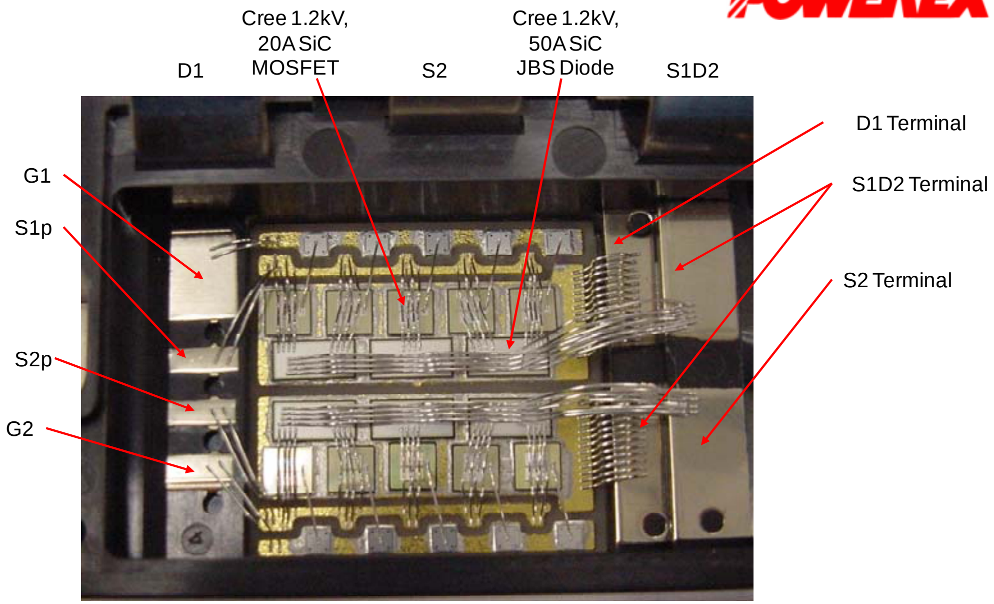
- 15kV Isolation
- Capable of 200C Operation
- Liquid Cooled

1.2kV, 100A SiC MOSFET/ SiC Schottky Half H-Bridge Module



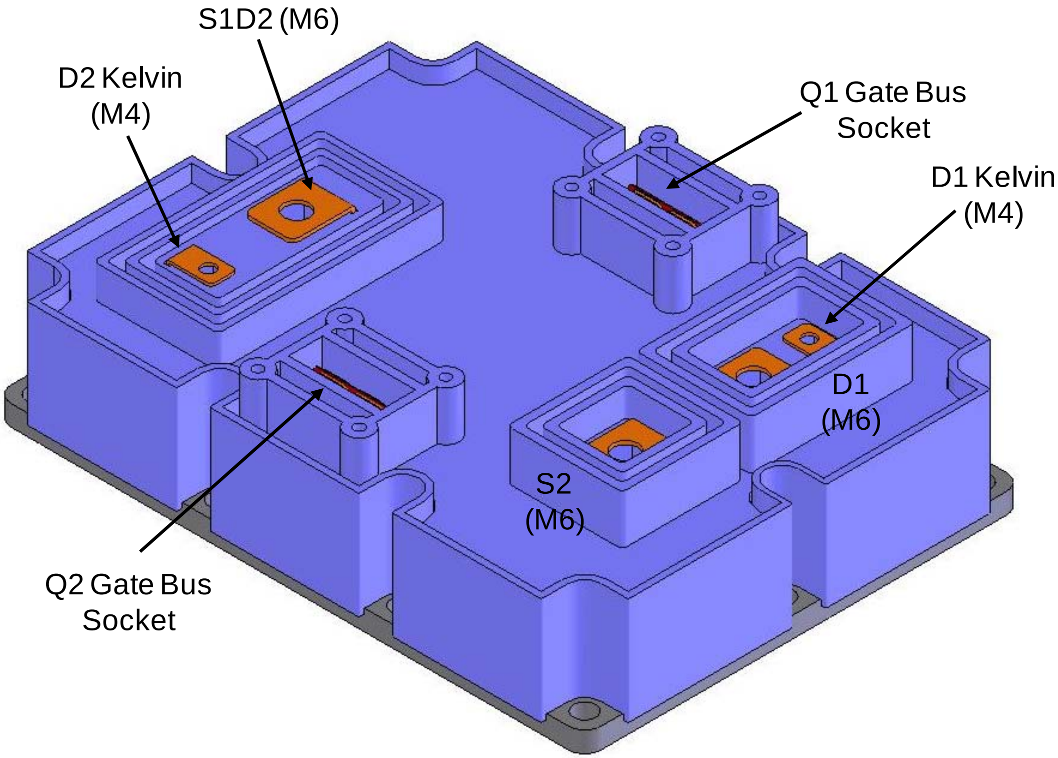
Capable of 200C Tj Operation





Technology Challenges for HV, HF Power Modules

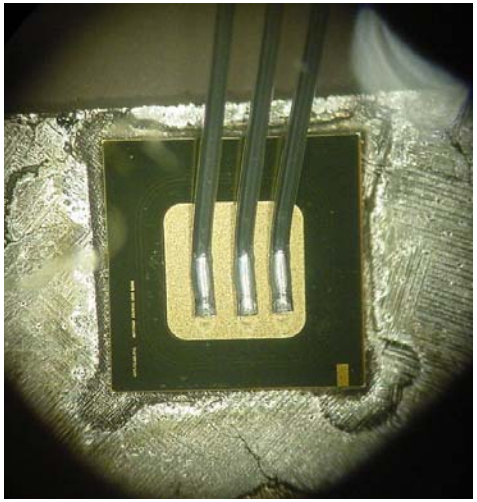
- External Voltage Strike & Creep
- Internal Dielectrics
  - Reliability & Losses
  - Corona/Partial Discharge
  - High Temperatures
- Low Inductance
  - Power Loop
  - Gate Loop
- Efficient Cooling
  - High Chip Power Densities
- Package Reliability

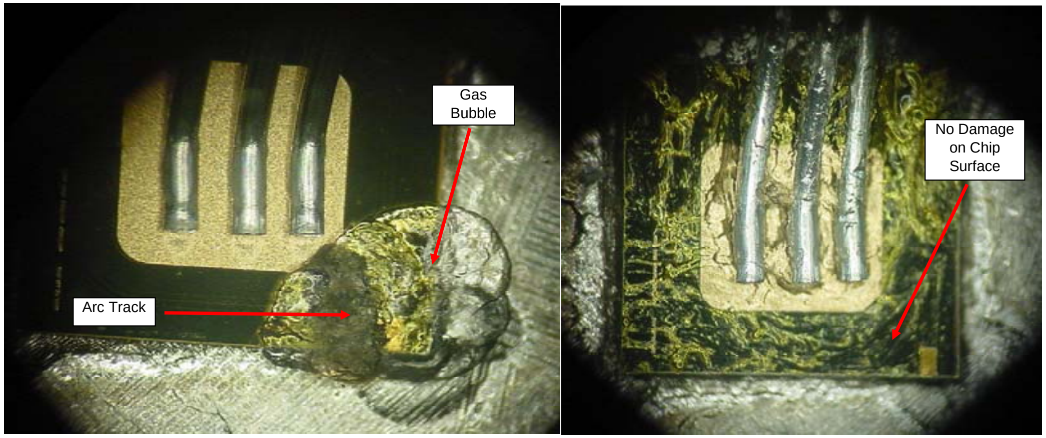


HPE Phase III SiC MOSFET Module:
10kV, 120A Half H-Bridge

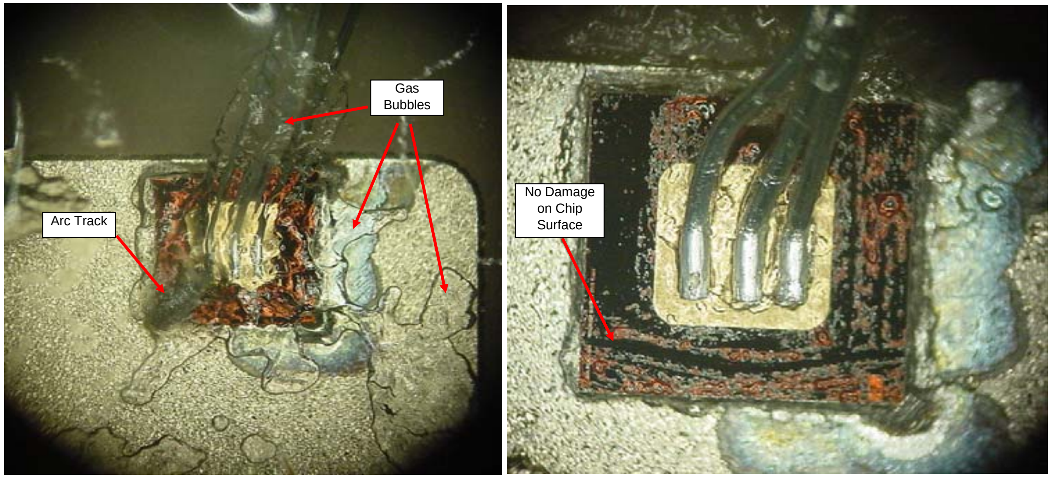
Internal Package Dielectric Material Challenges for HV/HF Modules

Start of HTRB Life Test





Gel Breakdown Failures Due to Bubble Formation



Program to Investigate & Improve Encapsulant Reliability Currently Funded by Navy MANTECH

NAVY MANTECH

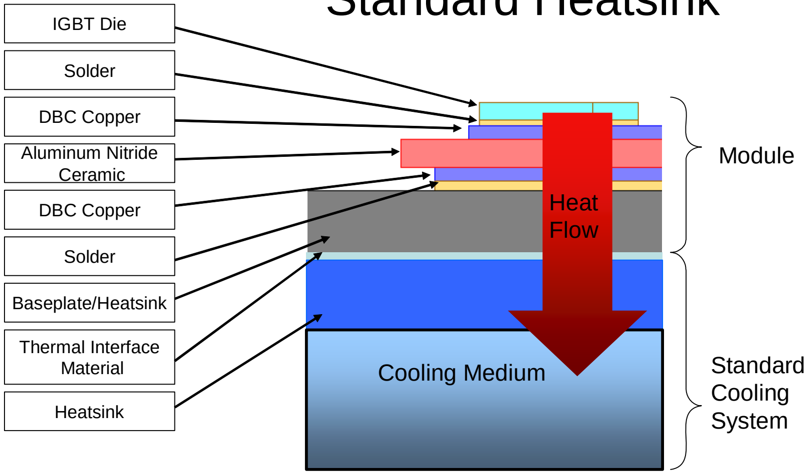
aci

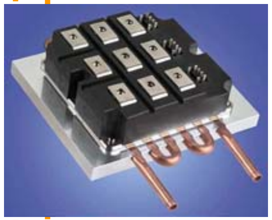
PENNSTATE ARL

POWEREX

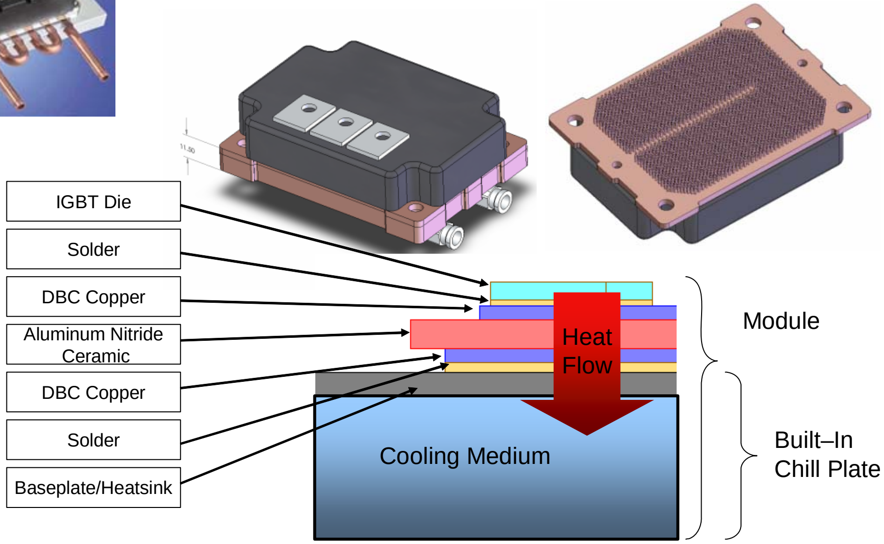
Cooling Challenges– Reducing the Heat Flow Path

Standard Heatsink

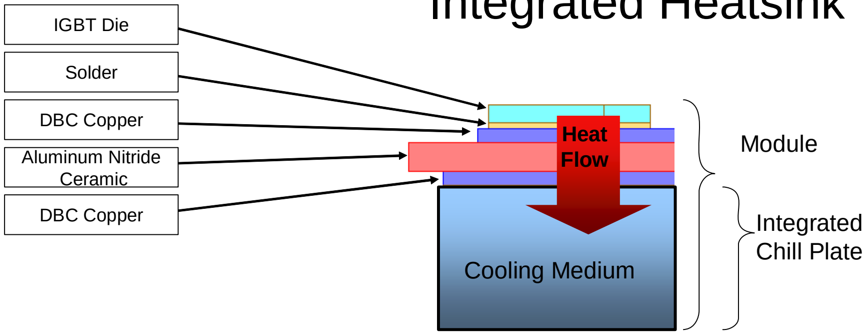


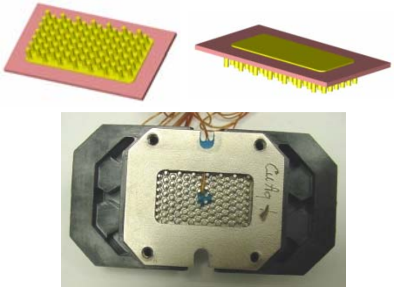


Built-In Heatsink

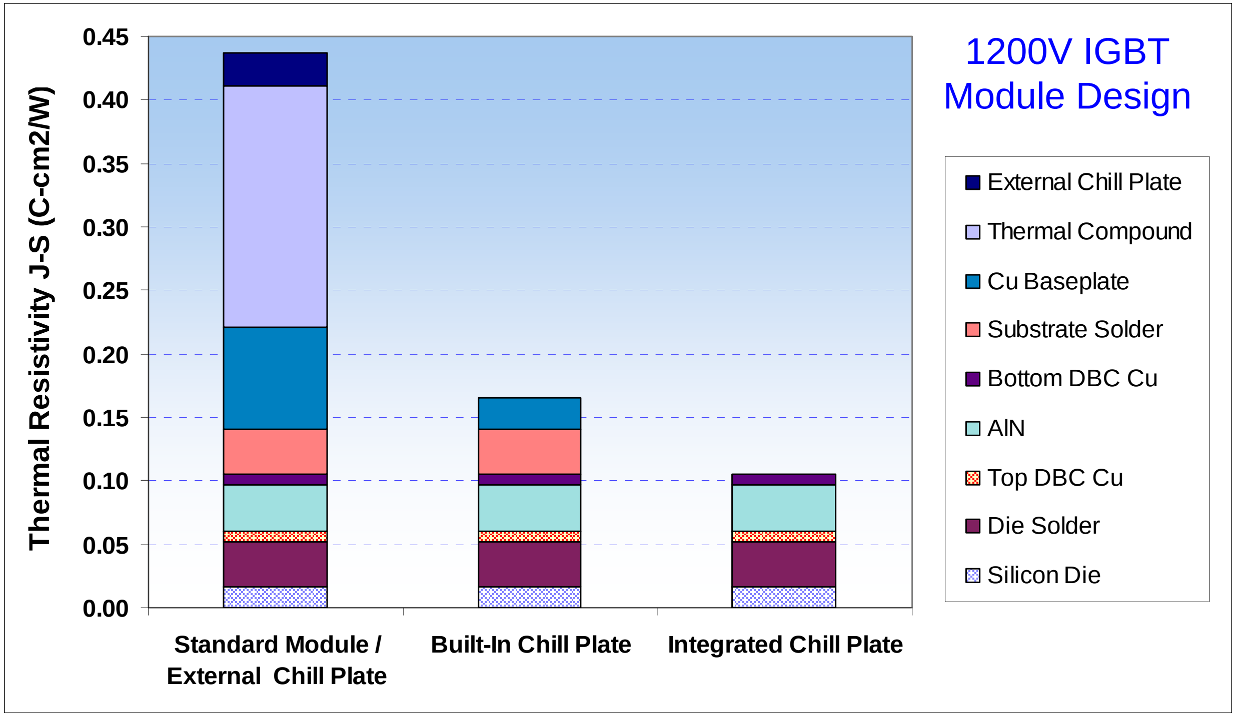


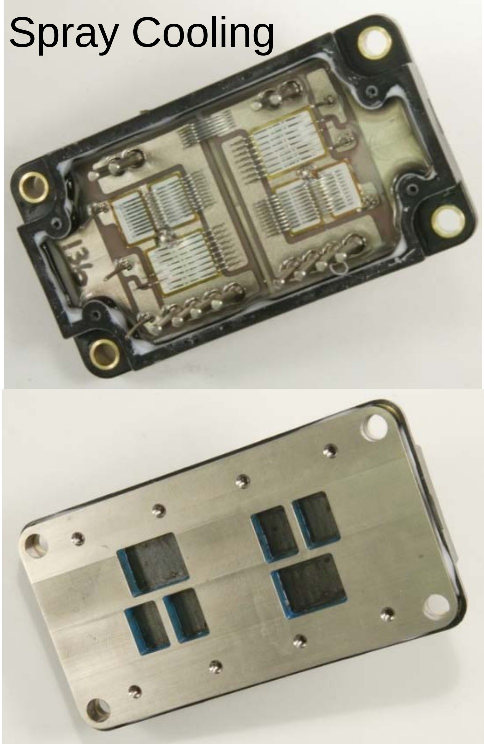
Integrated Heatsink



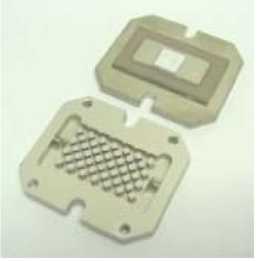


Thermal Resistivity Comparison of Paths to Cooling Medium

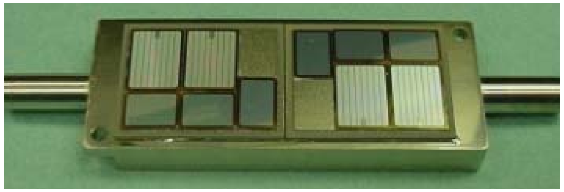




Programs Funded by DARPA, ONR, AFRL & DOE to Extend the State of the Art in Module Air & Liquid Cooling



Fins



Microchannels

Commercial Challenges For SiC-Based Modules

- SiC Chip Costs
  - High Material Cost
  - Low Yield
- Power Module Costs
  - Small SiC Die Sizes Leads to Lower Power Densities & Larger Modules

Advanced Power Modules & Packaging Technology

Scott Leslie
Chief Technologist

COMPONENTS AND TECHNOLOGIES FOR HIGH FREQUENCY AND HIGH AVERAGE POWER CONVERTERS*

HIGH MEGAWATT POWER CONVERTER WORKSHOP
NIST
GAITHERSBURG, MD

W. A. Reass
Los Alamos National Laboratory
P.O. Box 1663, Los Alamos, NM 87545, USA

April 8, 2008

Contact Information:
William A. Reass; Phone: 505-665-1013, E-mail: wreass@lanl.gov

* Work supported by the Office of Basic Energy Science, Office of Science of the US Department of Energy, and by Office of Naval Research

Outline

- Amorphous Nanocrystalline Transformers
- High Power Capacitor Development
- High Power Resistor Development

High Frequency Nanocrystalline Transformers Are Over 150 Times Lighter And Significantly Smaller (At Same Power)

HVCM Transformer

- 150 kV, 20 KHz
- 20 Amp RMS
- 1 MW Average (3) Present Use
- 450 LBS for 3
- 3 KW Loss At 2 MW
- “C” Core Design (Parallel Windings)

Typical H.V. Transformers

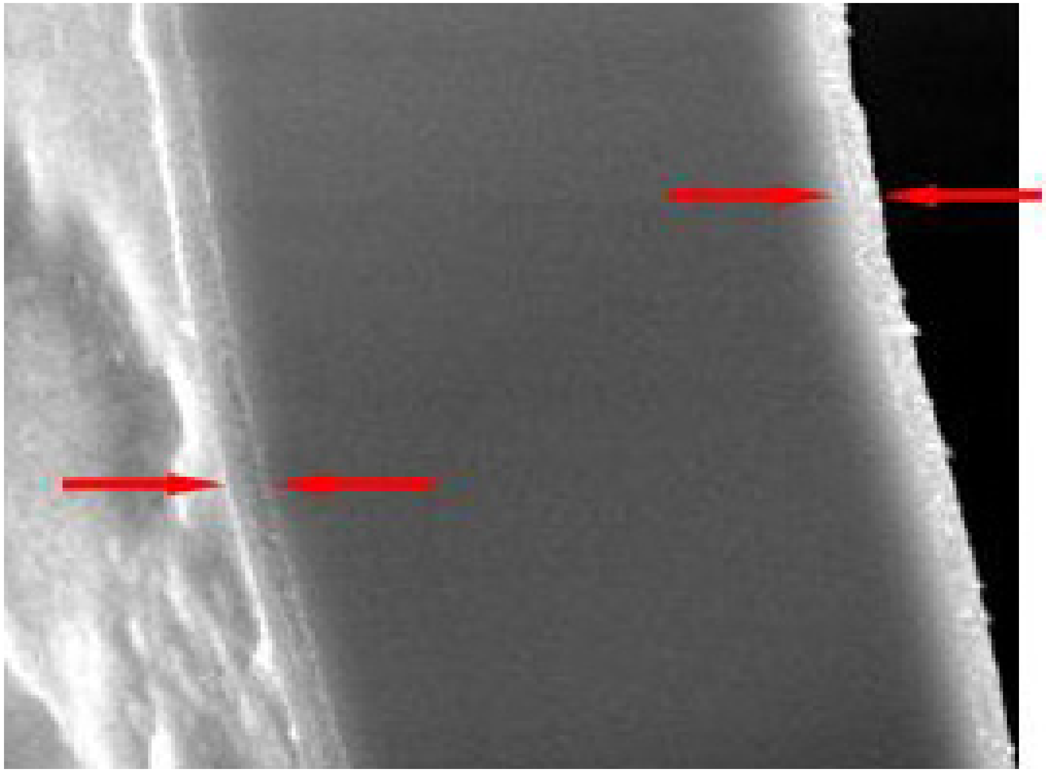
- 100 kV, 60 Hz
- 20 Amp RMS
- 2 MW Average
- 35 Tons
- ~30 KW Loss

Nanocrystalline Transformer Development

- Funding Initially Provided To Develop Process Techniques
  - Winding (Nano Shrinks ~1.5% During Processing)
    - Loose
    - Compressible Mandrel
- Processing (Exothermic Reaction)
  - Oven Temperature Control
- Stack Lamination Insulation
  - Wet Lay-Up
  - Dry
- Core Cutting
  - Water Jet, EDM, Diamond Saw
- Core Annealing
  - Dimensional Stability
- Pole Face Lapping, Etching
  - Pole Face Stack Resistance
  - Eddy Current Losses

Nanocrystalline Transformer Development

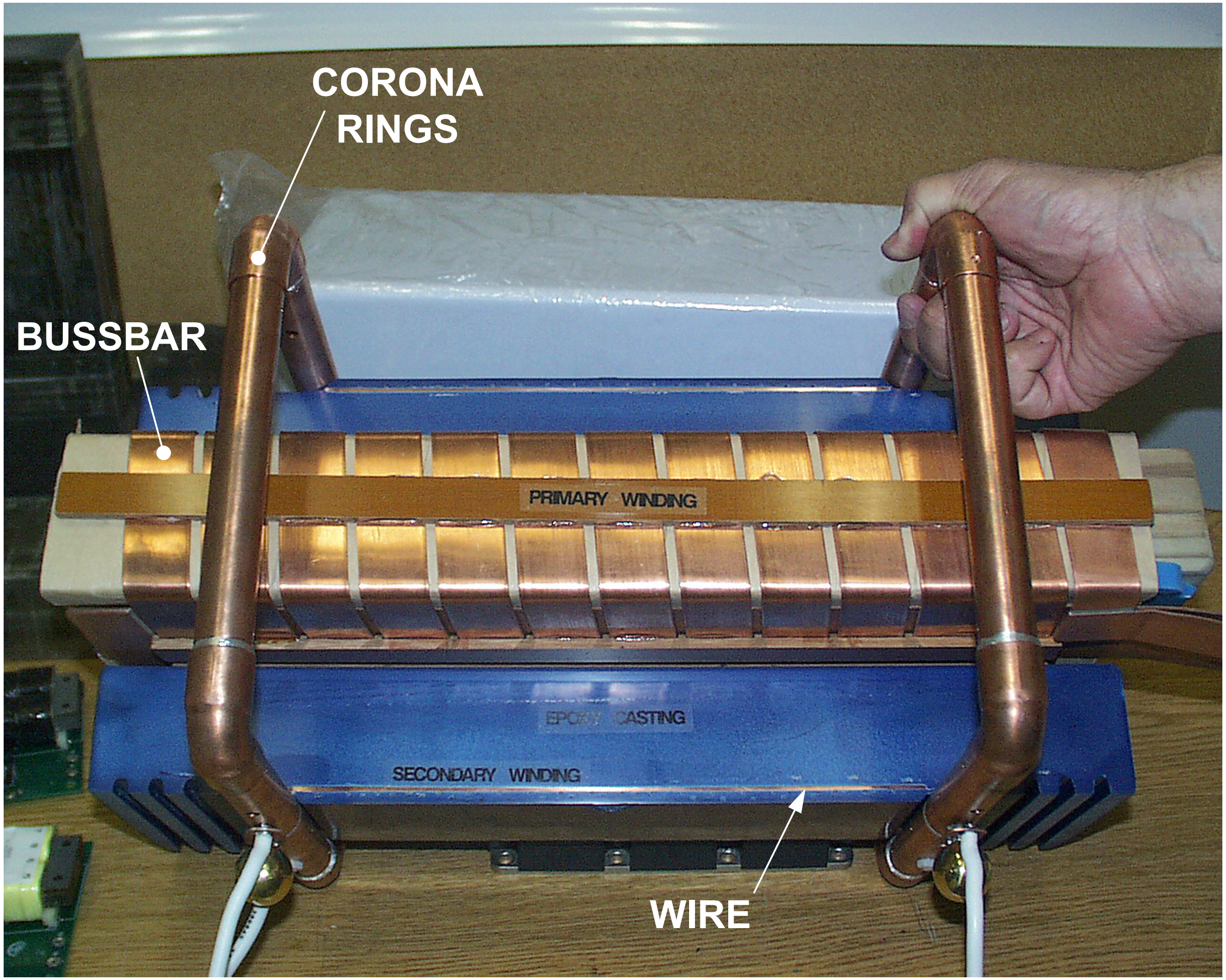
Oxide Insulating Coating



Nano Material Characteristics

Mu	100,000
Lamination Thickness	.0007"
Lamination Insulation	<1 µM
Stacking Factor	~90%
Bsat	12.3 kG
Core Loss (our use)	~300 W
Core Weight (our use)	~95 lbs
Power (each core)	330 kW

Boost Transformer Winding Design (140 kV, 20 kHz)



Recent Developments

- Wider Strip Width
  - – Improved Core Geometries
- Improved Manufacturing
  - – Better Experience Base
    - Better Mechanical Fabrication Techniques
    - Can Manufacture Exotic Shapes
- Improved Electrical Performance
- More Vendors
  - – Japan (Hitachi)
  - – Russia
  - – Germany (VacuumSchmelze)
  - – China

Advanced Transformer Geometry

- Polyphase Y
- Ring And Bar
- Triangle And Bar

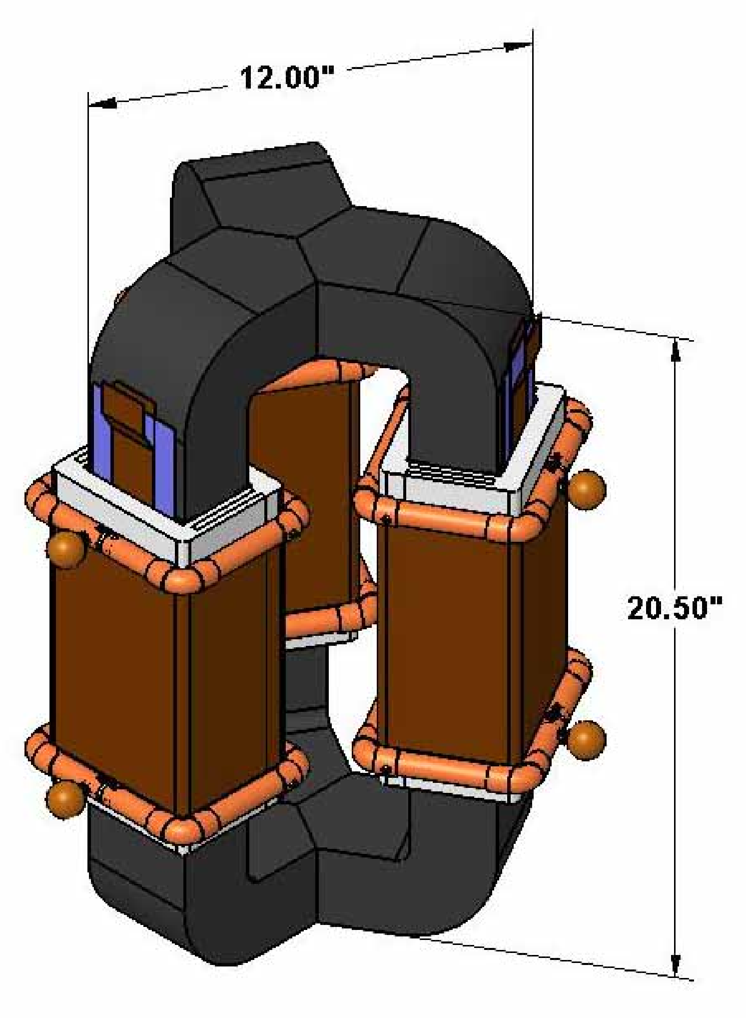
Polyphase Y

ADVANTAGES

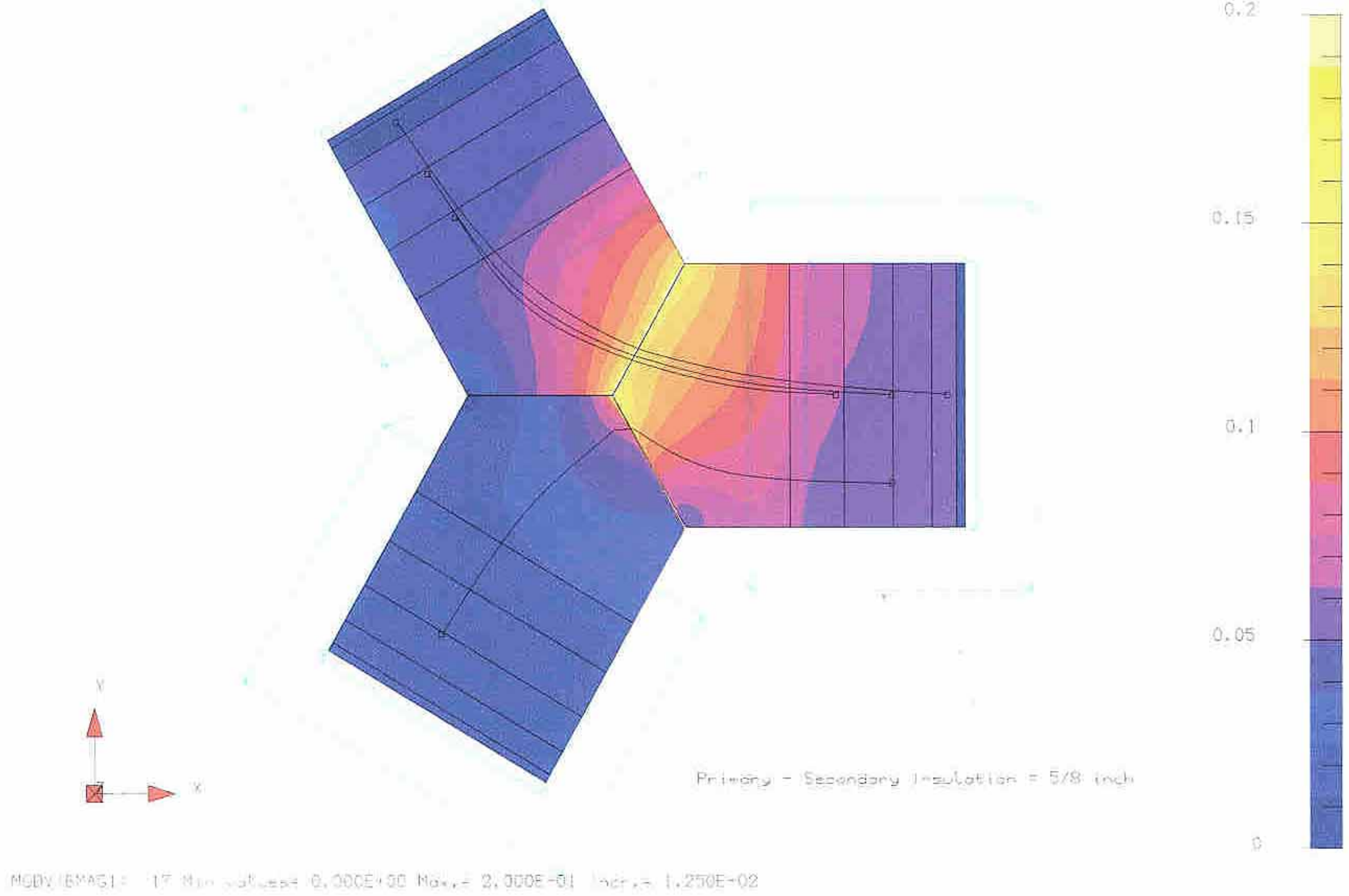
- Good Flux Balance
- Highest Performance
- 2 Gaps Per Winding Pair

DISADVANTAGES

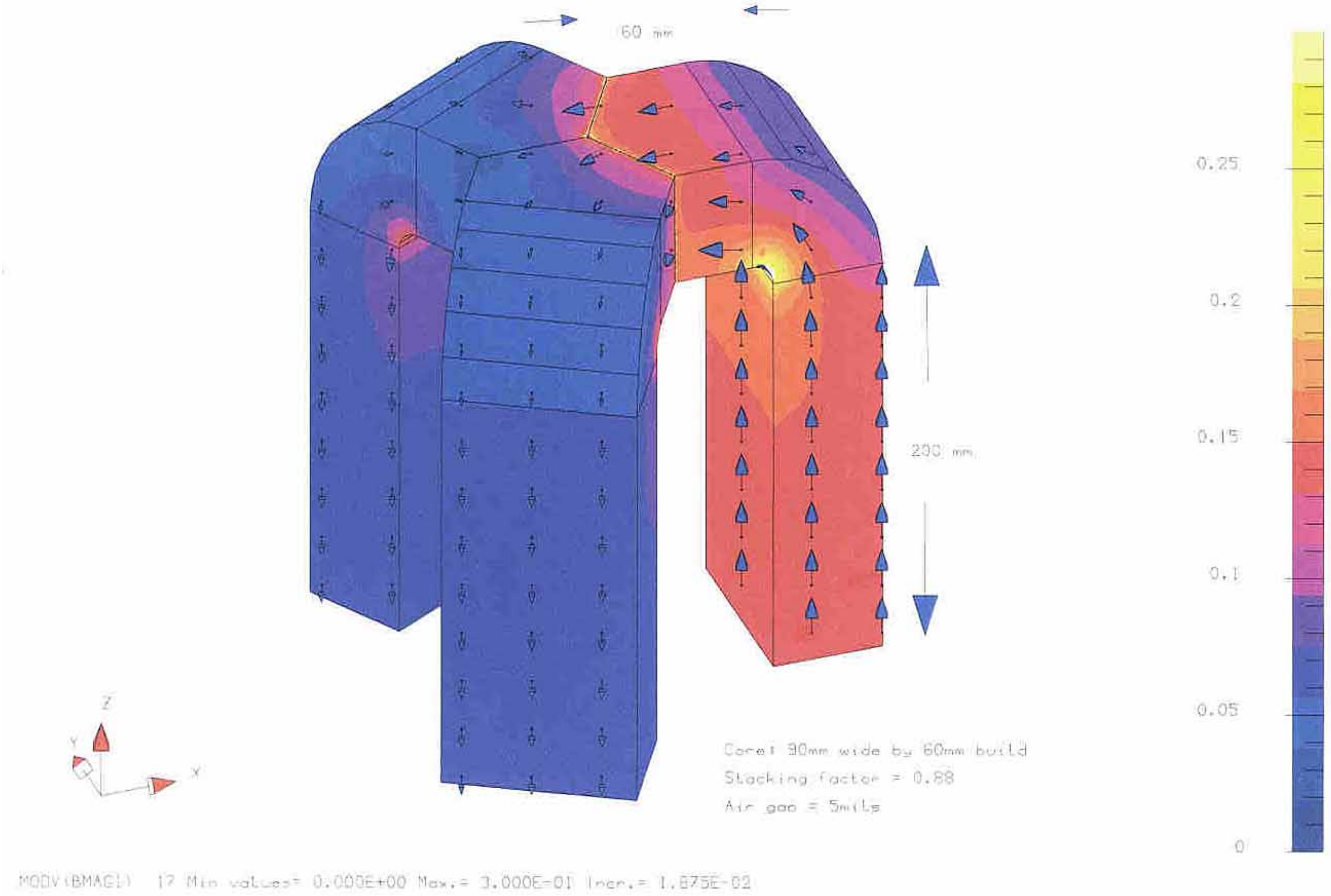
- Windings On Core
- Hard To Manufacture
- Sensitive To Tolerances
- Could Not Manufacture Previously



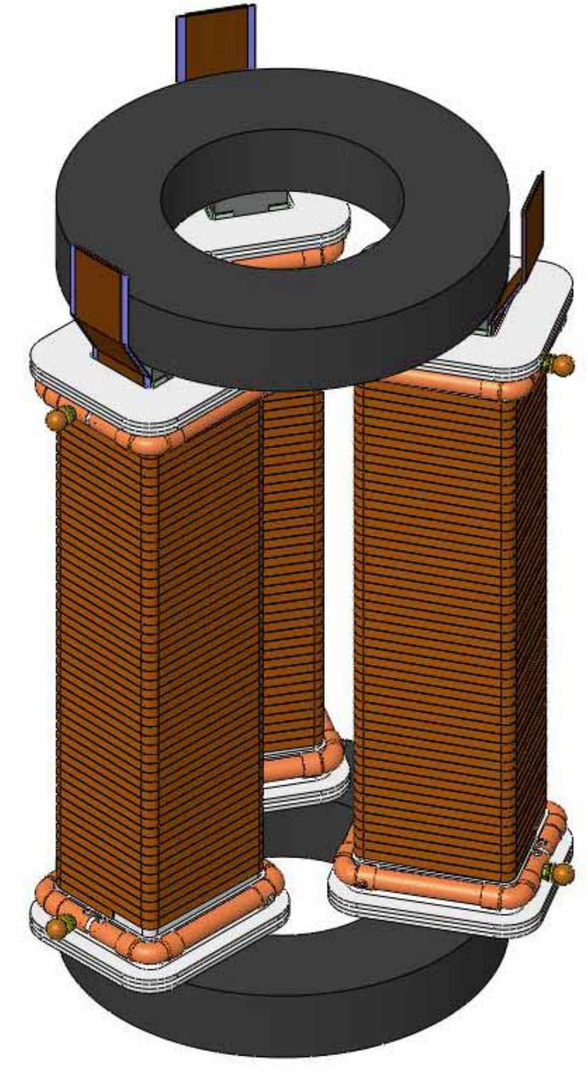
Flux Asymmetry Caused By Chamfer



Flux Concentration On Inner ID



Ring Bar Transformer



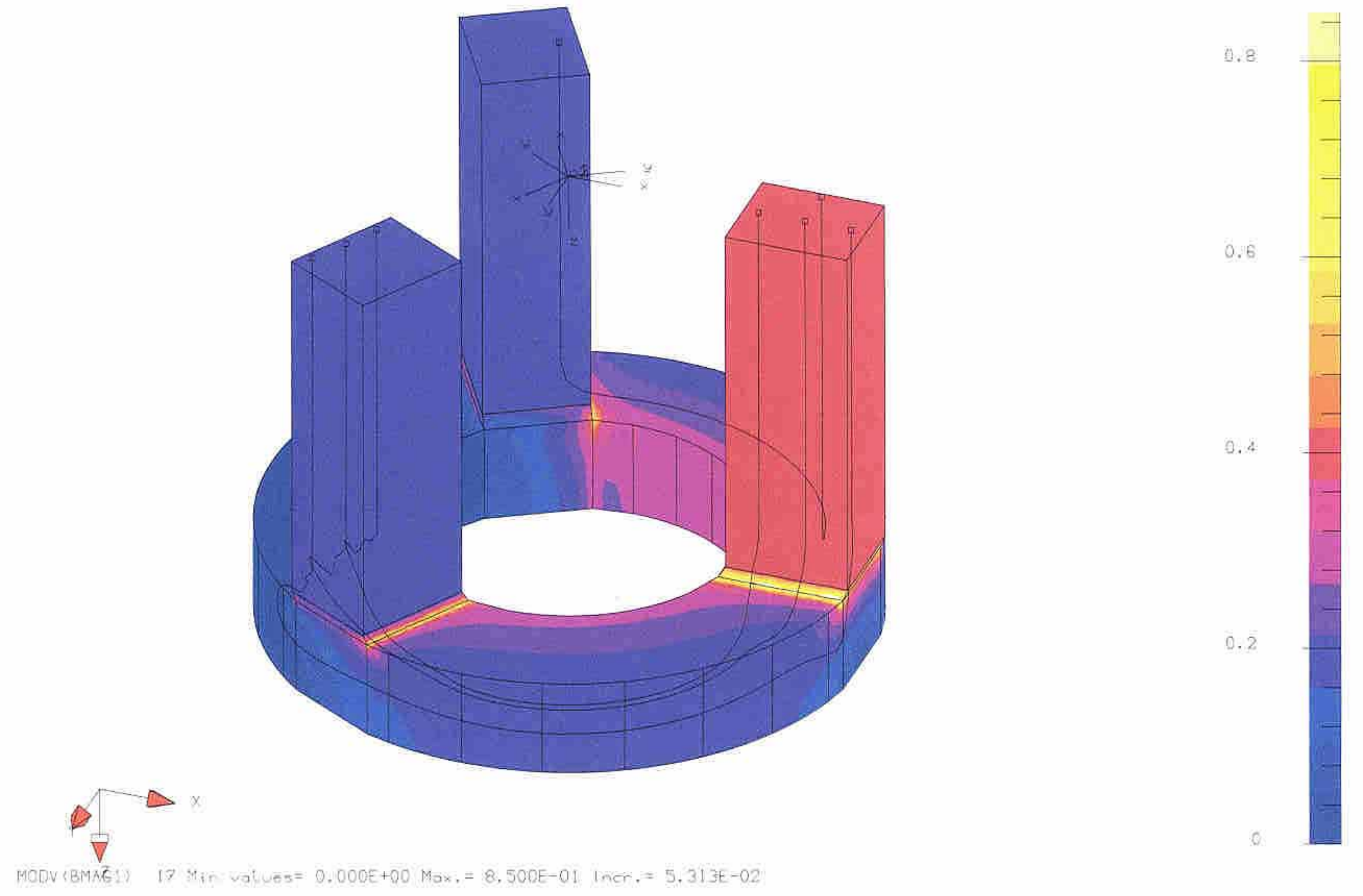
ADVANTAGES

- Simple Topology
- Can Use Winding Bobbins

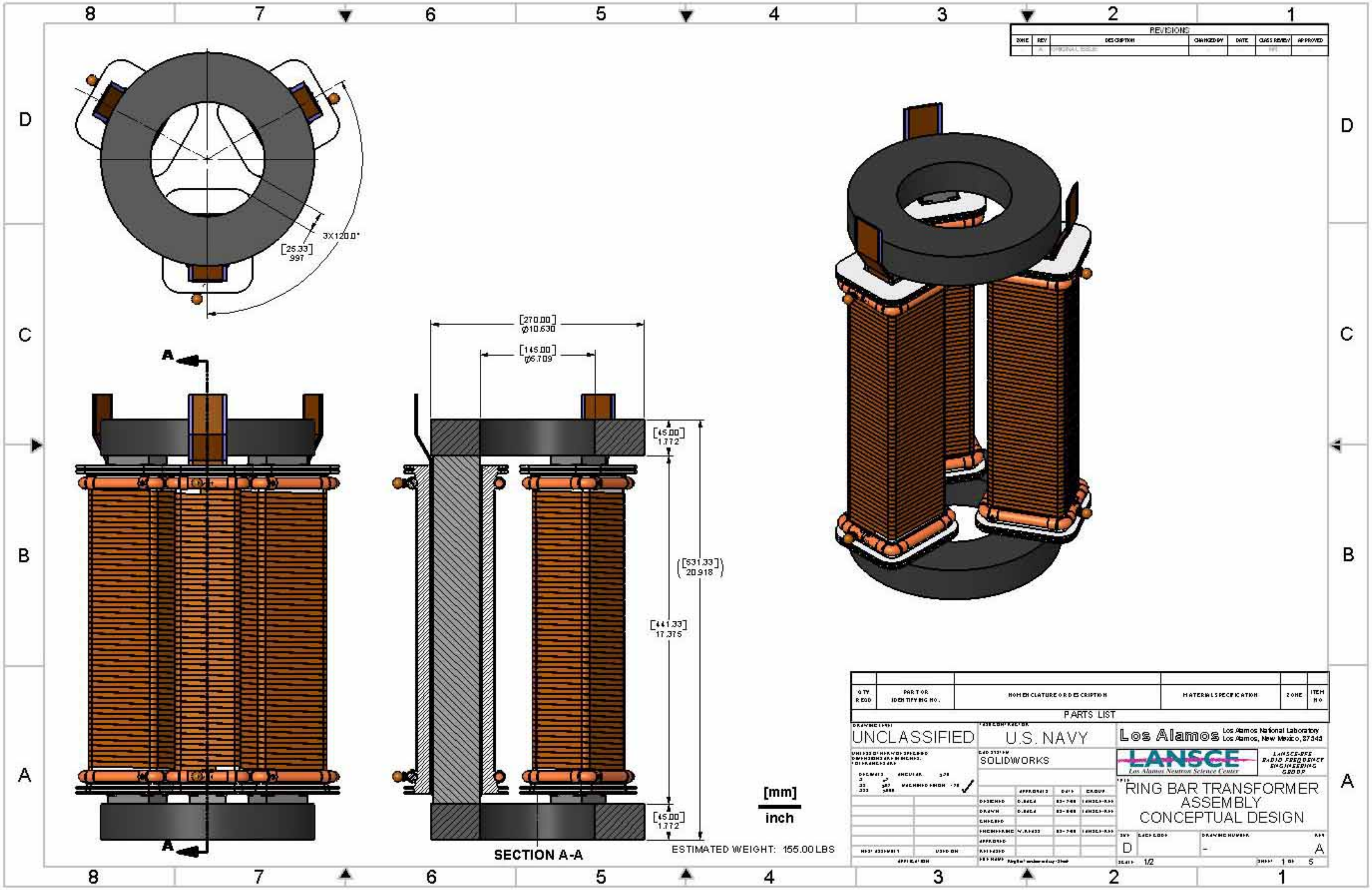
DISADVANTAGES

- Higher Reluctance Path
- 2X Core Gaps
- Mechanical Robustness (?)
- Secondary Tabs On Narrow Dimension

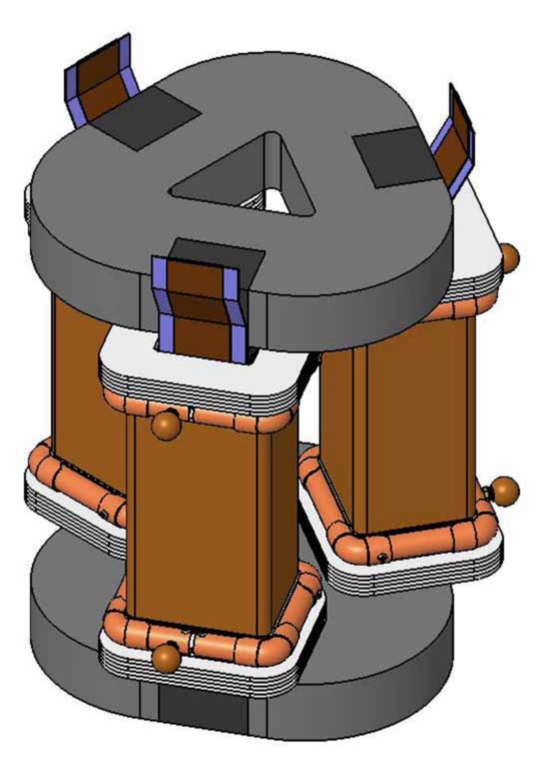
High Flux Concentration At Interface



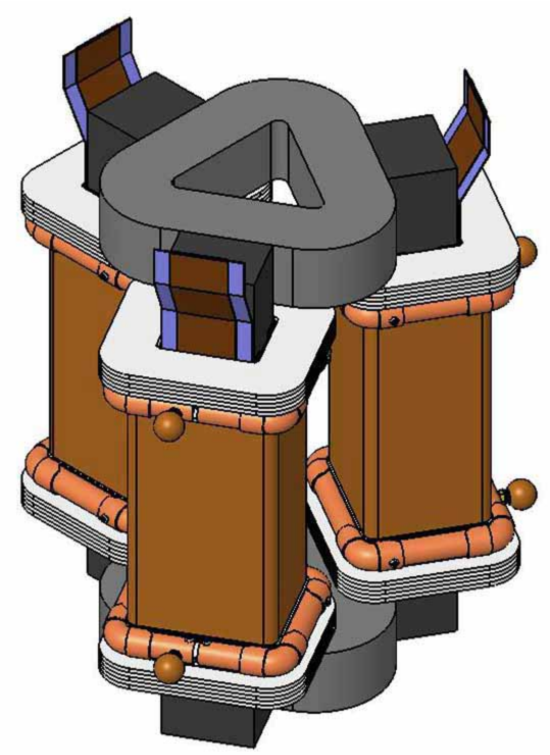
Ring Bar Transformer–Conceptual Design Drawing 1



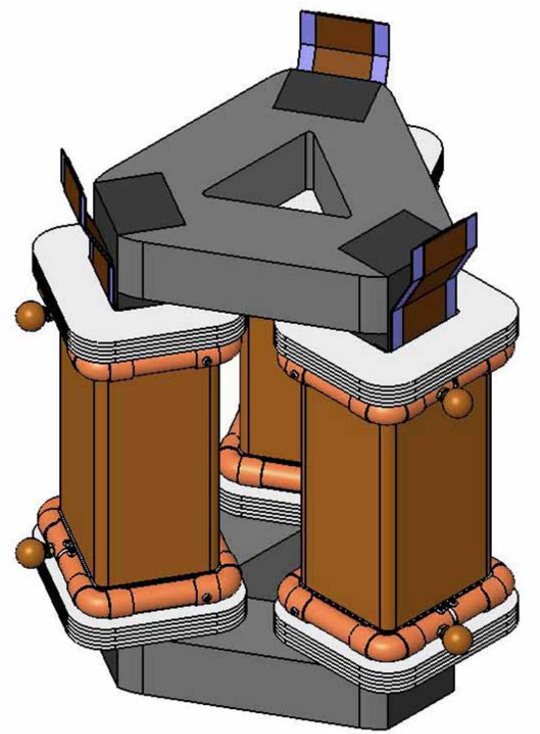
Triangular Bar Transformer Design Possibilities



OPTION 1



OPTION 2



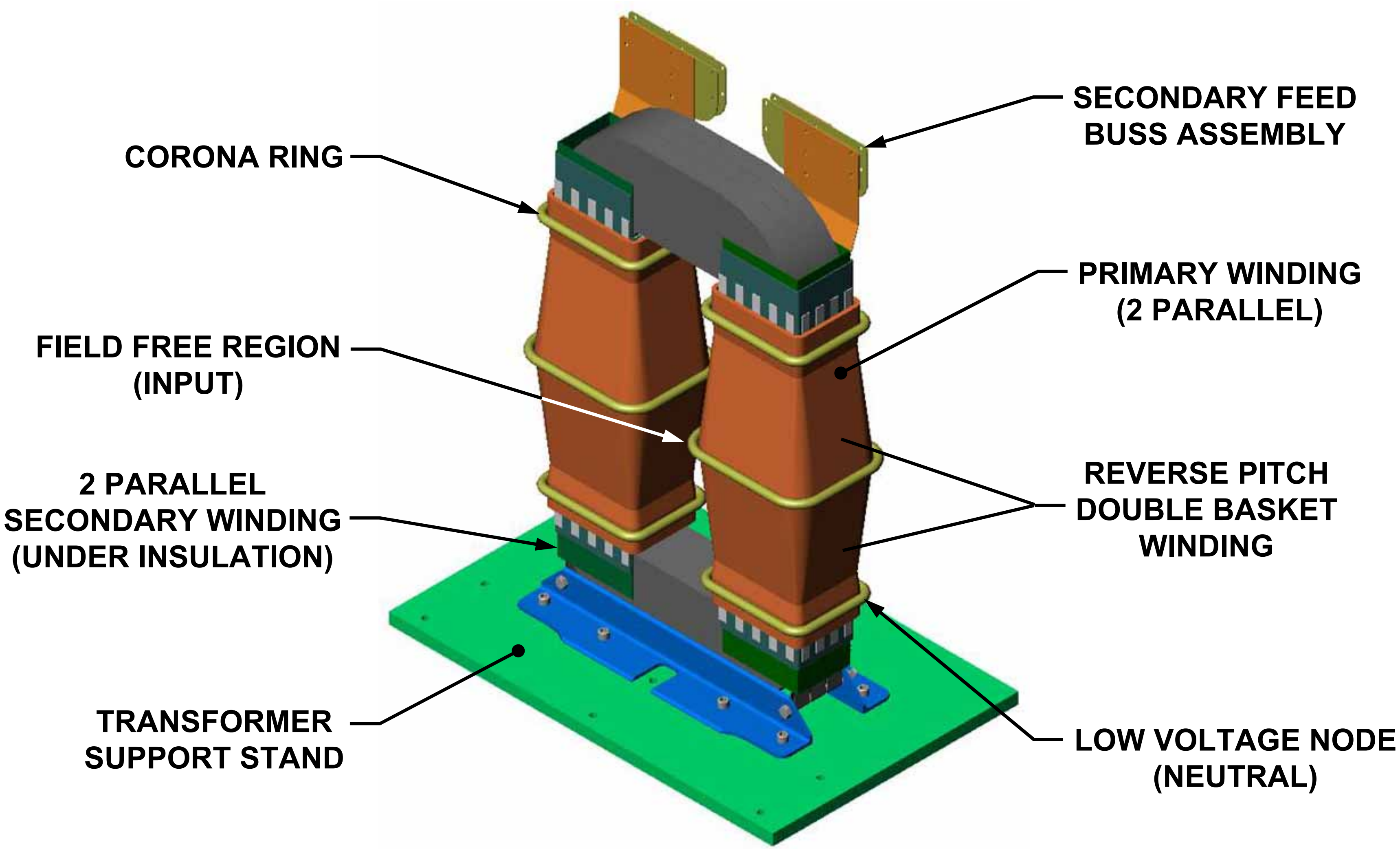
OPTION 3

Flux Concentration At Corner And Interface

Design Example of a 13.8 kV “Y” Input, 460 V “Δ” Output with a 2.7 MVA Overall Electrical Rating (Advanced Core Design)

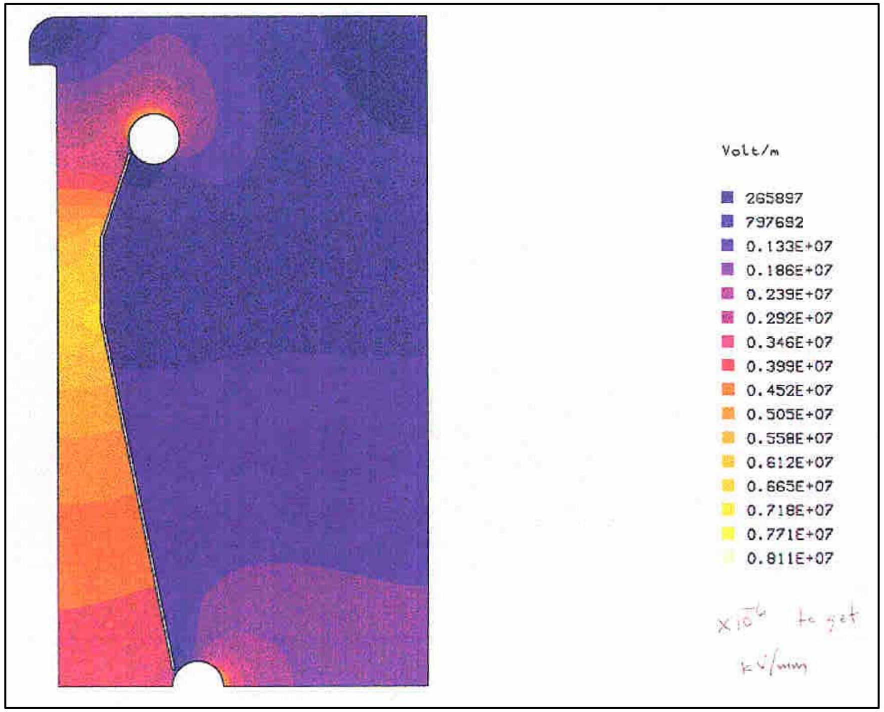
- Core Loss
  - 20 KHz And ~7 KG
  - 30 W / lb (125 lb)
  - ~4 KW
- Primary Loss
  - 2 KW
- Secondary Loss
  - 4 KW
- Overall Efficiency
  - ~99.6%

C-Core Designs Offer Higher Efficiency

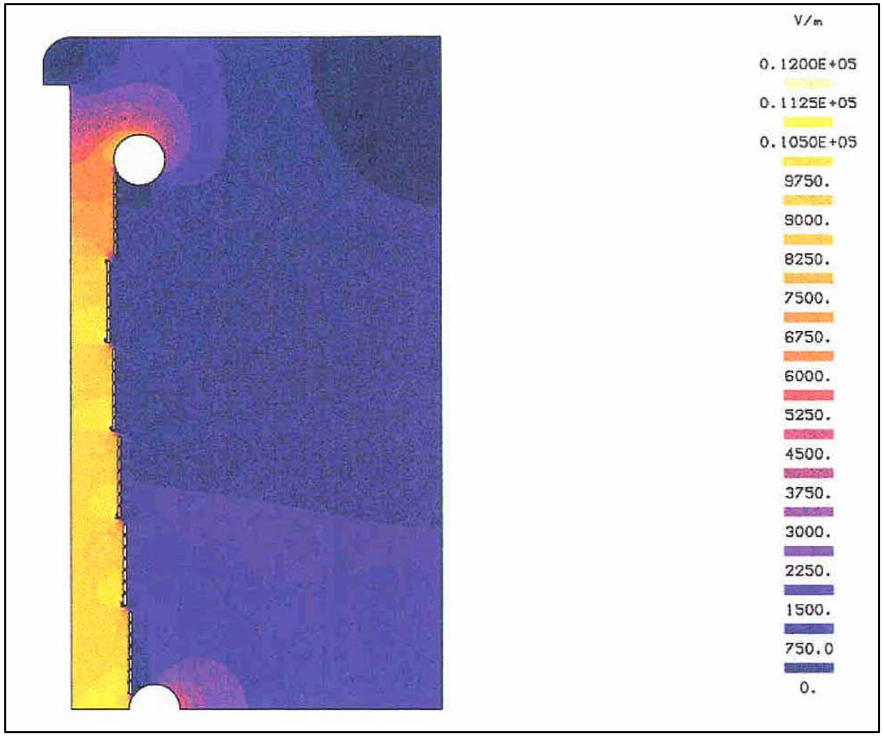


Advanced Winding Topology Minimizes Field Stresses And Leakage Inductance

Winding Taper Improves Performance



$\times 10^{-6}$ to get kV/mm

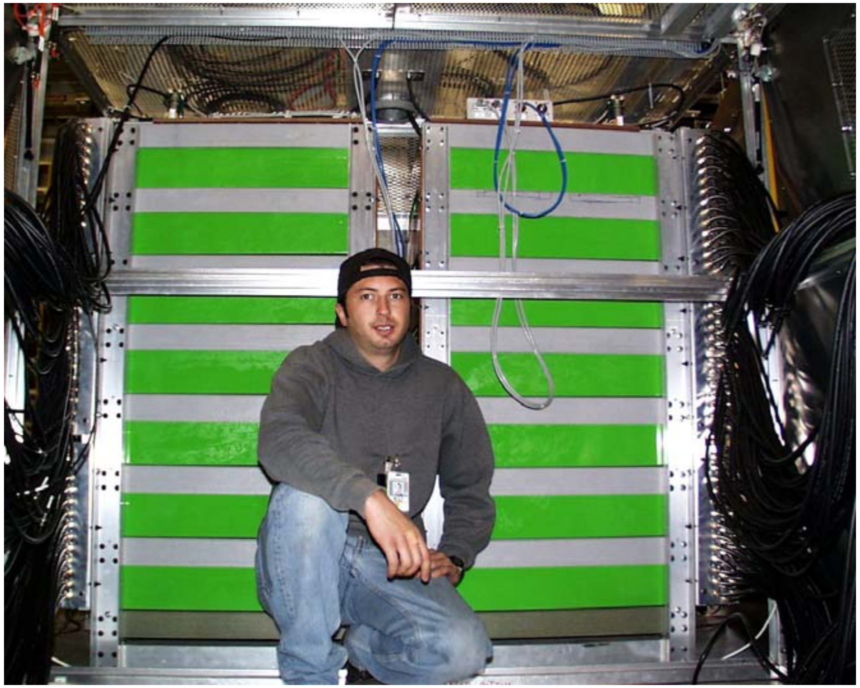


- Lower Field Stress
- Lower Leakage Inductance
- Minimized End Effects

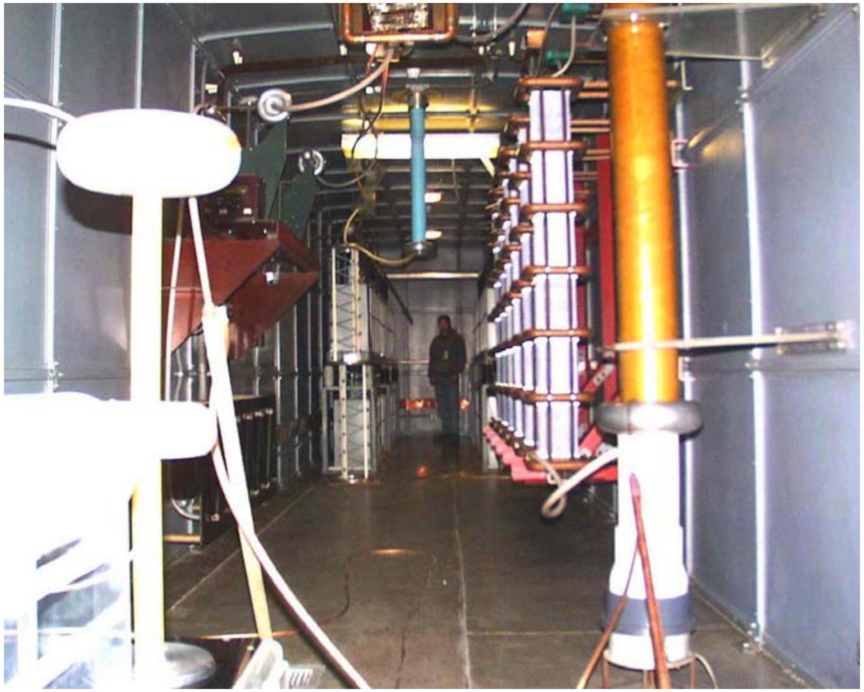
What We Need to Also Consider

- Examine Start-up Sequence To Prevent Core Saturation
  - Prevent Excessive Fault Currents
- Examine Neutral Node Commutation Transients
- Examine Core Pole Piece Interface Design To Minimize Flux Concentration And Losses
- Optimize Design to Application For Increased Efficiency
- Optimize Winding Design For Minimized Field Stress And Leakage Inductance

Self-Healing Metallized Hazy Polypropylene Energy Storage Compared To Conventional High Voltage Method (Paper and Foil) Is Very Compact And Reliable

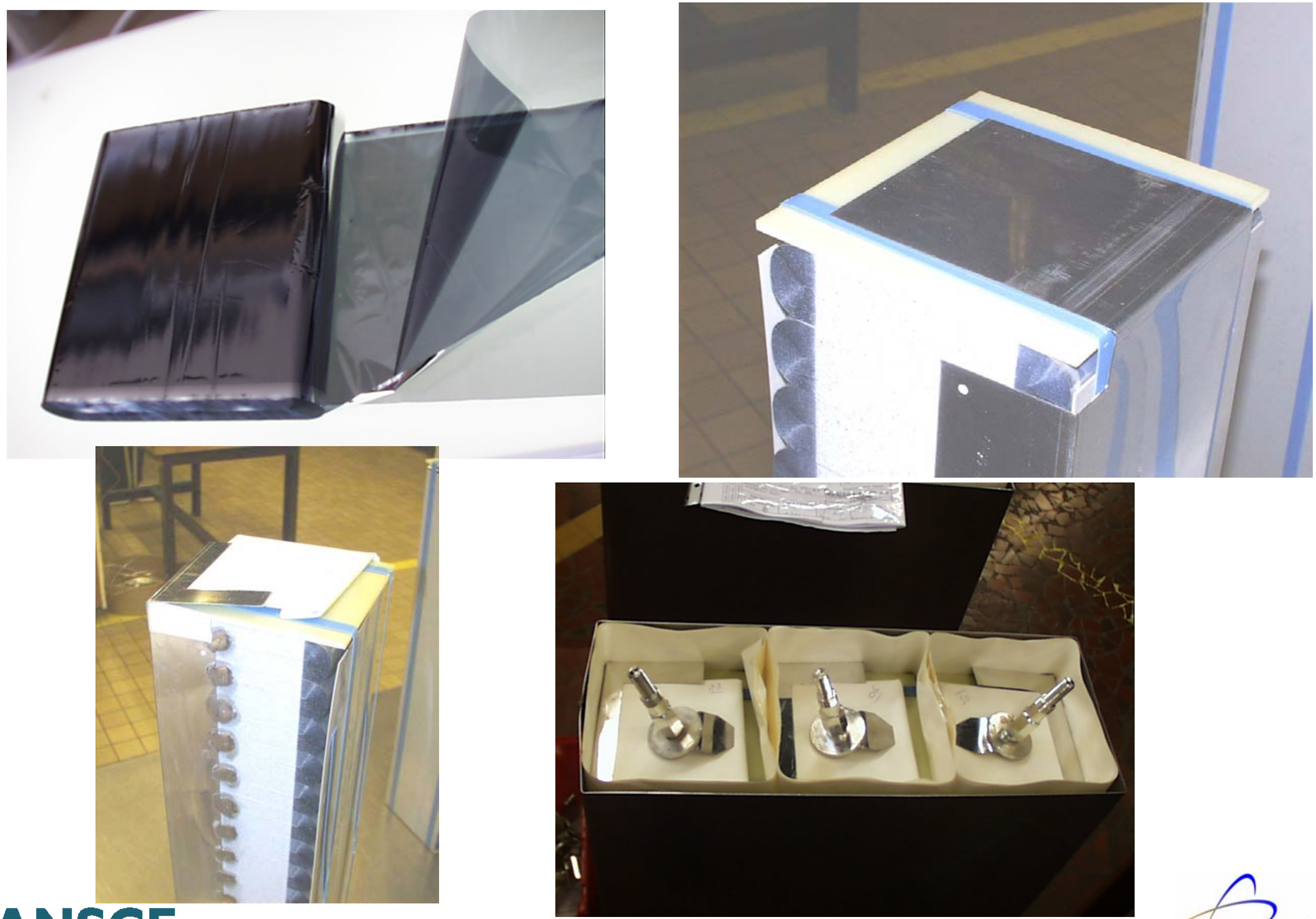


- 300,000 hour lifetime
- Graceful degradation
- High frequency design
- High volumetric efficiency
- High safety factor



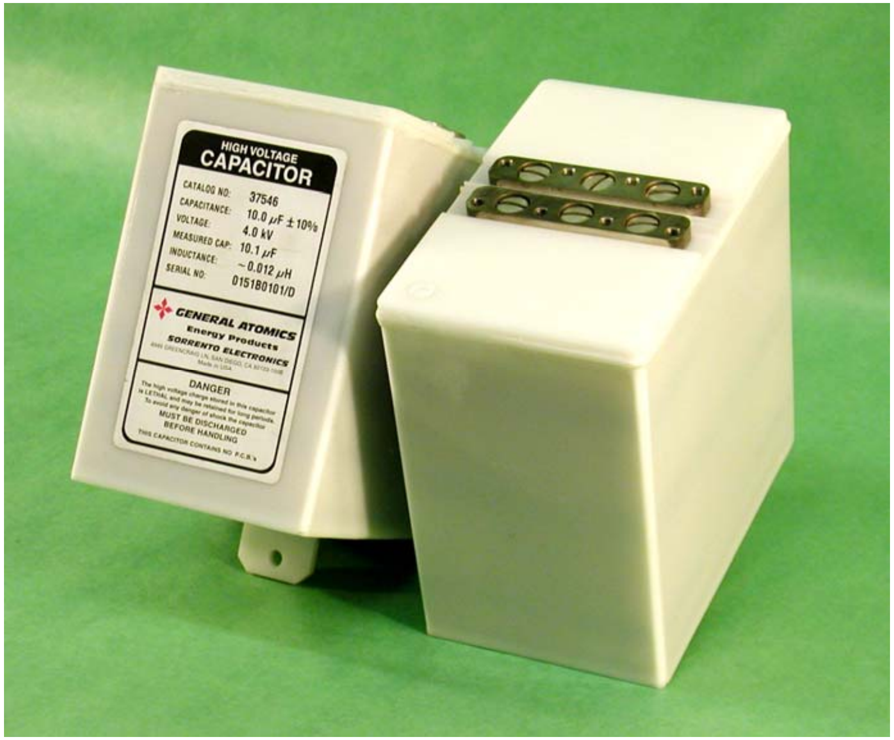
- Limited lifetime
- Explosive failure modes
- Highly frequency dependant and lossy
- Large footprint
- Poor safety factors and dangerous

Ultra-Low Inductance (L~ 15 nH) 20 kHz High Current DC Buss Link Self-Healing Capacitor Construction



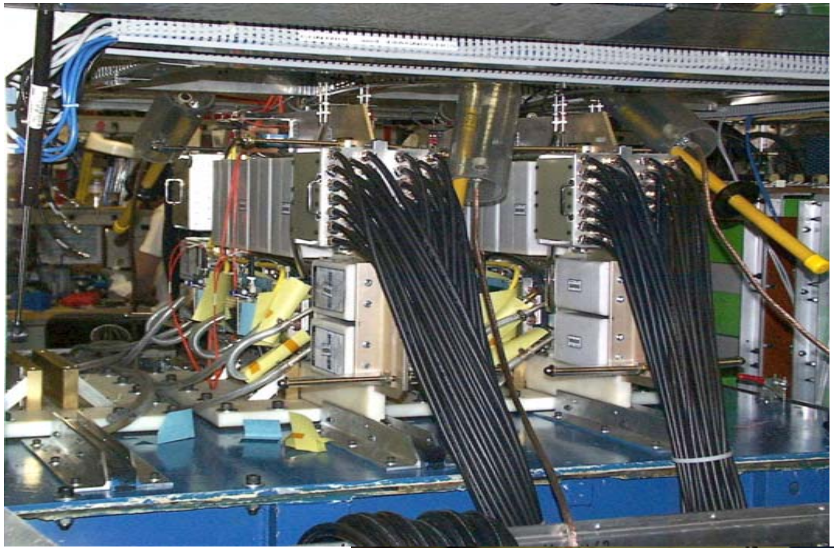
General Atomics High Power Foil Capacitors

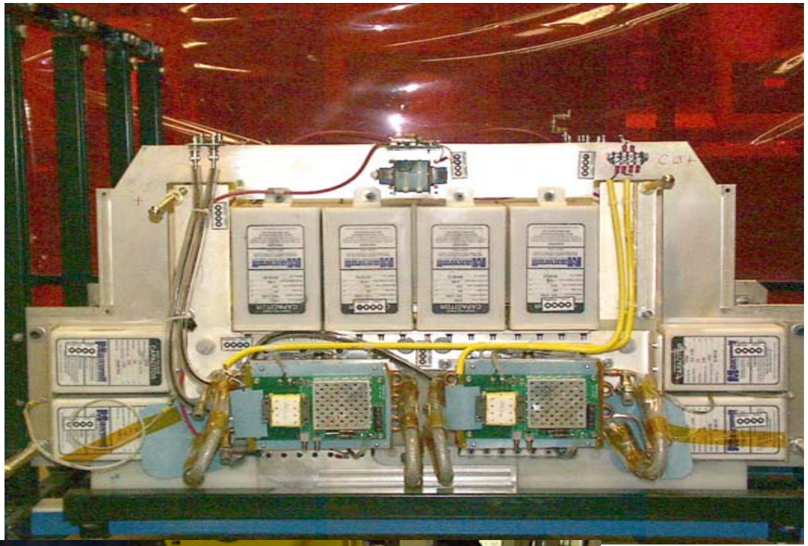
Transformer Resonating Capacitor
3100pF, 120kVDC, 85kVAC,
3.5 MVAR
(Composite Dielectric)

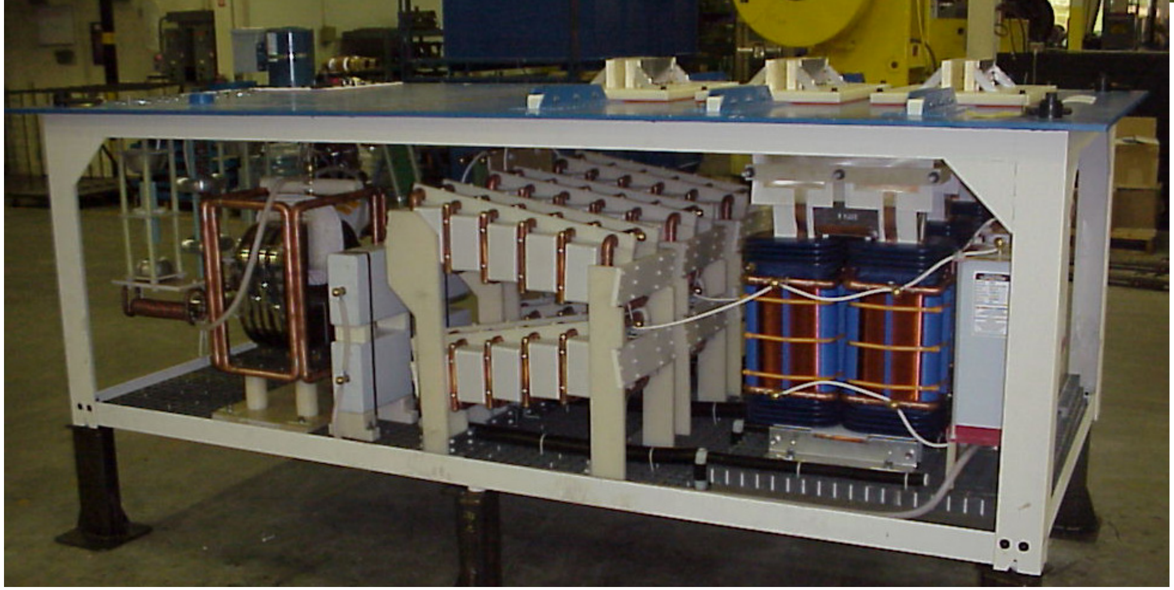


IGBT Bypass Capacitor
10µF, 4kV
250 ARMS @ 20KHz
(Plastic Dielectric)

Example of High Power Capacitor Use (10 MW Long Pulse Polyphase 20 kHz Resonant Converter)







Recent Capacitor Improvements

- Improved Winding Techniques
    - Smaller

- Improved Dielectric Oil
    - Lower Loss

- Better Understanding of System Requirements

- Thinner Dielectrics

- Recent “Record” Energy Densities in Polypropylene Pulse Power Capacitors

- Other Programmatic Pushes

- Many Players

High Power Resistor Development

- Many Types of Resistors
  - Film
  - Wire Wound
  - Ribbon Wound
  - Carbon Composition
    - Organic
    - Ceramic
- All Suffer From Problems
  - Inductance
    - Wound varieties
  - Voltage Gradient or Current Density
    - Composition (grain boundary issues)
  - Film
    - Energy (Fault) Capability
- Power Resistors Are Not Desired
  - May be useful in (high power) snubber circuits

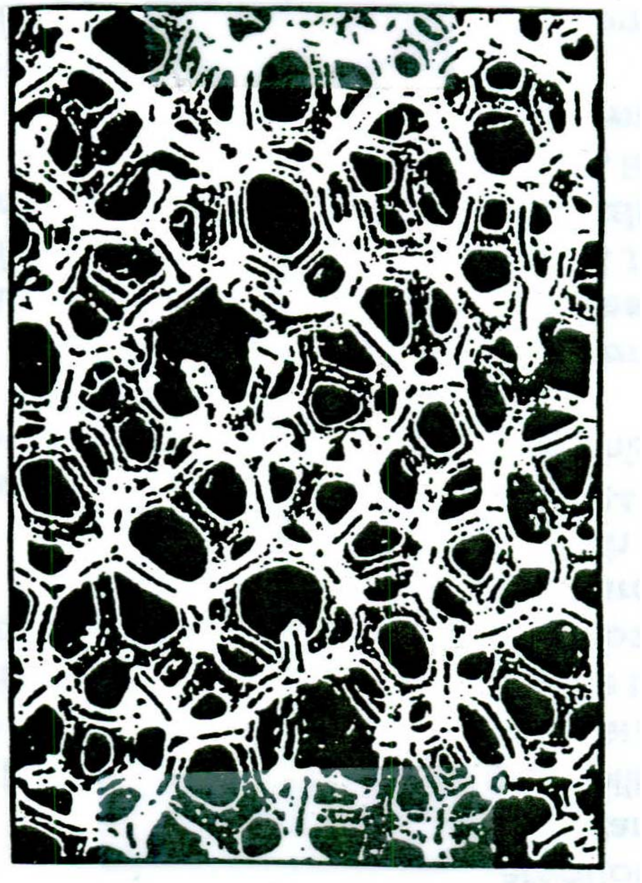
Reticulated Vitreous Carbon (RVC) Foam High Power Resistors Developed at LANL

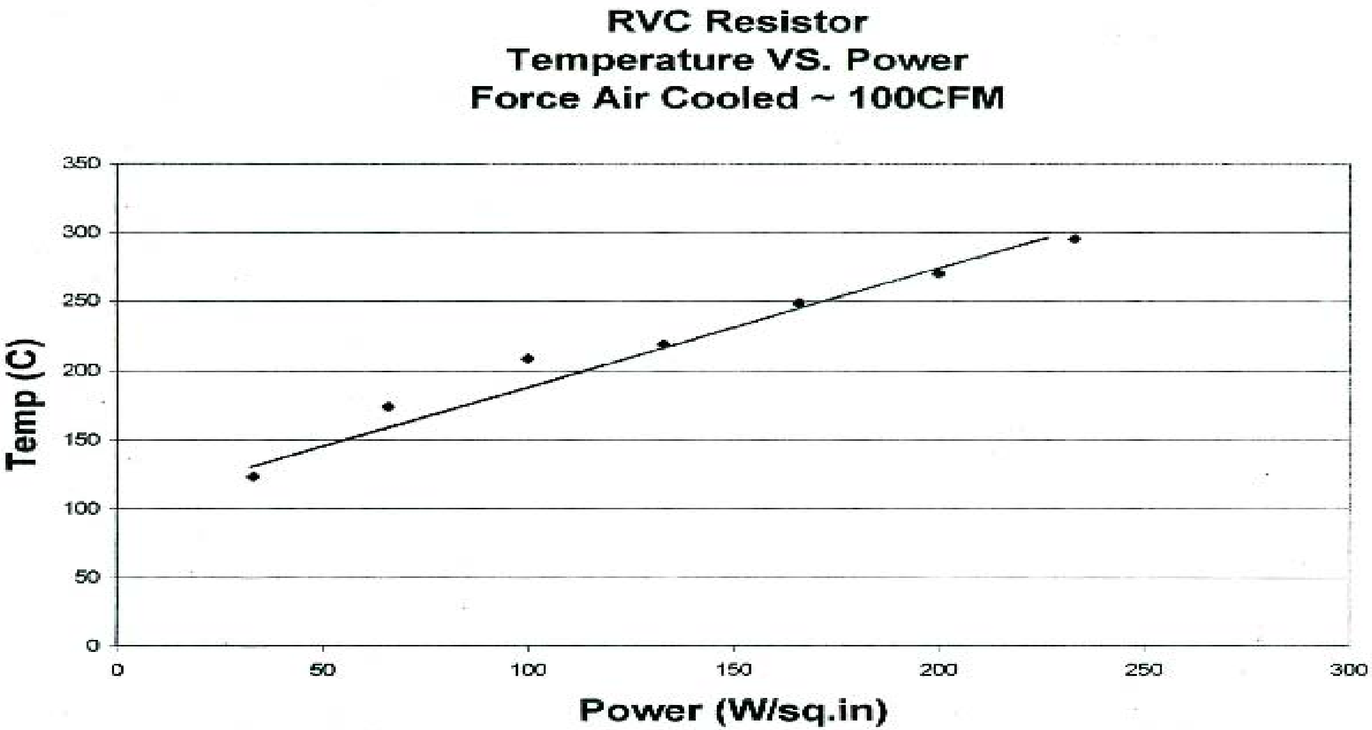
- •A Glassy Carbon Available with Various Ligament Diameters, Porosities, and Densities.
  - •Can engineer low inductance, high power resistors

- •LANL Has Tested To:
  - •>15 kA / cm2
  - •Pulsed Currents to 850 kA
  - •Circuits to 120 kV
  - •130 J / cc in air
  - •25 J / cc in oil
  - •250 W / sq in (air)

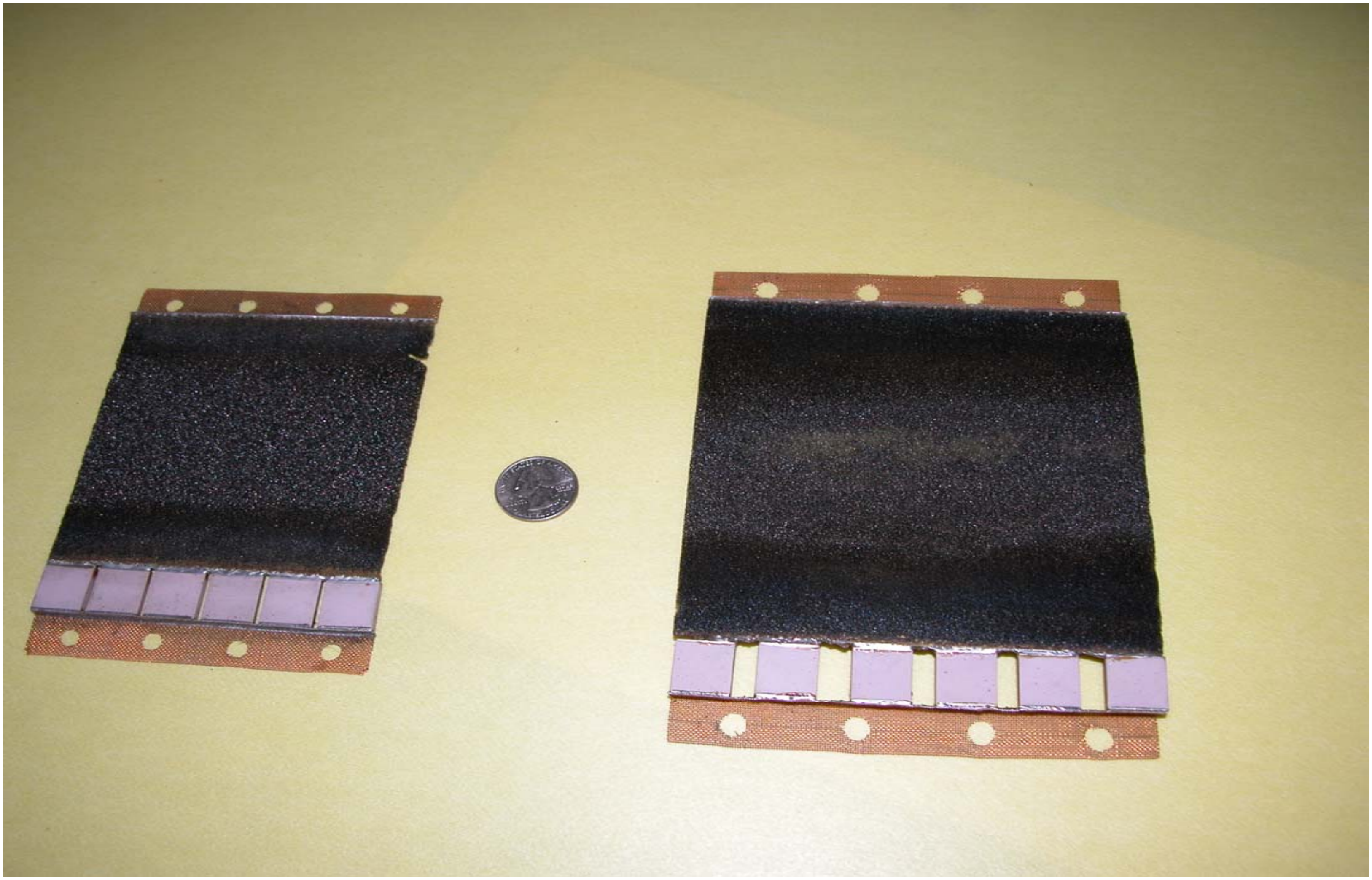
- • "Δ" R = 0, Does Not Absorb Oil or Water

- •Has "Infinite" Surface Area, Should Be Capable of "Infinite" Power




RVC Resistor
Temperature VS. Power
Force Air Cooled ~ 100CFM
Temp (C)
350
300
250
200
150
100
50
0
0
50
100
150
200
250
300
Power (W/sq.in)

EXAMPLE OF “RVC” LOW INDUCTANCE HIGH POWER SNUBBERS



CONCLUSION

- MANY TECHNOLOGIES DEVELOPED FROM EUROPEAN TRACTION MOTOR INDUSTRY
  - WE CAN LEVERAGE THOSE COMPONENTS TO OUR DESIGNS

- MANY CONVERTER TOPOLOGIES AND TECHNIQUES DEVELOPED BY U.S. INDUSTRY

- COMPLEMENTARY TECHNOLOGIES ALSO DEVELOPED AT THE NATIONAL LABORATORIES
  - High Average Power Systems
  - Pulsed Power Systems

- NATIONAL LABORATORIES ARE AVAILABLE TO HELP
  - Teaming is part of our charter.

Role of inverters in grid of the future

need larger, faster inverters to supply additional attributes

need students to hire from consortium – to become graduates and serve industries… form consortium

Big role in future to support separate islands on the grid

dist + residential side of inverters

micro grids need to be at residential area to control area

Inverters need to be considered in relation to entire system
High-bandwidth real time control of real and reactive power on grid

need standards
- com
- SAFETY
- Interconnection
- Within grid and within inverters

Use high bandwidth devices to increase transmission line capability through stability enhancements… and to access useable thermal capability within loss constraints

Inverters 2

Renewables and islands aren't co-located… need transmission capabilities to connect them

IEEE has subcommittees on islanding, one that focuses on generators > 10 MW
Another on Intentional islanding

Achieve markets for future inverter attributes

- Spinning reserve
- Voltage regulation
- VARS
- Sag mitigation'
- Active filtering (harmonics)
- ramp rates

storage
Phase balancing

100 MW Static VAR compensators are being added by utilities.

EERE working on value of attributes

Regulators must recognize value of attributes

Eastern utilities buying selling small quantities of VARS

Dynamic VARS can be produced by wind generators and peaking turbines
1547.4 is a forward battleground (islanding)

Excel Energy $5 M investment in NaS bat for storage

Smart grid does not have to be a complex grid

Key development Requirement (1 MW → 100/200 MW Inverters)

Lower cost
better reliability
Bandwidth capability

SiC-based components
Control systems for inverters
Better plastics in packaging that lasts more than 10-15 years.

Technology Gaps, components, systems, etc

No big technology gaps other than above

Need standards that can accommodate attributes of advanced inverters

1547.3 communication standards for DG

Need to evolve from existing utility requirements

Cree needs guidelines in terms of what products to SiC based products to develop

Micro-grids should have eight 9's reliability

Better simulation models need to support system development

Voltage levels are increasing

~~~~~~~

DOE has SmartGrid Committee. Should this ad hoc group (us) become associated with smart grid committee

DOE needs to participate in demonstration of technologies and DOE has $100 Million/year to support demonstration of smart grid

~~~~~~~

Potential Role within IEEE

Address overview of Workshop at IEEE PES national meeting in Pittsburgh in July

What should we don next… would this group be willing to draft a roadmap?

Lee

Le

Bob

Charlie

Jason

George

Madhav

Frank

Maric

Alex

Dave

sumit

How do we do the roadmap

Commonalities of different applications

Need summary of related activities … e.g., all programs in smart grid

Literature search in commonalities

coordinate with IAPG

There are things that can have a big impact if we can agree upon:

- If SiC came in at cost of siX5 that would be a big game changer
- High bandwidth devices would be a big asset
- Communication control and standards