UNITED STATES DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
Gaithersburg, Maryland 20899-

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Dear Workshop Attendees:

On behalf of the workshop organizers, I would like to thank you for attending and participating in the High-Megawatt Converter Workshop held at NIST on January 24, 2007. The enclosed CD contains the viewgraphs presented by each speaker† as well as the workshop proceedings summary† prepared by Ron Wolk.

For convenience, the CD contains a file in the top level directory called "*Indexed Proceedings*" that contains all of the files in an indexed format. Links to referenced presentations are also provided within the proceedings text. The "*Indexed Proceedings*" document is best viewed with a recent version of Acrobat Reader (e.g., version 8) so that the links are opened in a separate window. The multiple window format (tile or cascade) is controlled using the "*Windows*" pull down menu on the Acrobat Reader Toolbar. The "*files*" directory on the CD contains the Acrobat Reader 8 installer, as well as, the individual presentations and workshop "*Proceedings Summary*" document used to produce the "*Indexed Proceedings*" document.

The High-Megawatt Converter Workshop has been very beneficial to the ongoing interagency effort between NIST and the DOE Office of Clean Energy Systems in identifying technologies requiring development to meet the power converter cost and performance goals for the DOE SECA and FutureGen near zero-emission fuel cell power plant programs. Based upon the consensus of the workshop attendees, an industry-led high-megawatt power converter roadmapping effort is being planed, and an interagency working group is being formed to coordinate Federal programs in the high-megawatt converter area.

We look forward to your participation in future high-megawatt converter activities.

Best regards,

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† The content of the CD represents input from the participants and does not necessarily represent the opinions of the National Institute of Standards and Technology, the DOE Office of Clean Energy Systems, nor the US Army ERDC-CERL.

NIST

Proceedings of the High Megawatt Converter Workshop

January 24, 2007
National Institute of Standards and Technology
Gaithersburg, MD

Sponsored by
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List of Abbreviations

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

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

1. Summary

On January 24, 2007, a group of forty-two Power Conditioning Systems (PCS) experts invited by the National Institute of Standards and Technology (NIST), the Department of Energy (DOE) Office of Clean Energy Systems, and the ERDC-CERL assembled at a High Megawatt Converter Workshop held at NIST headquarters in Gaithersburg, Maryland. An Organizing Committee consisting of Dr. Samuel Biondo (DOE), Dr. Allen Hefner (NIST) and Frank Holcomb (ERDC-CERL) recommended the invited participants and presenters. The objectives of the Workshop were to exchange information focused on state-of-the-art technologies for High Megawatt Converter systems, discuss the merits of proposed approaches to achieving significant cost reduction and improved DC to AC electrical conversion efficiency, discuss how Federal resources could potentially be utilized in a coordinated effort to address these issues, and to discuss the merits of establishing an industry-led Roadmap Committee to offer guidance that could facilitate the achievement of the desired goals.

Markets

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

Promising Areas for Improvement of PCS Cost and Performance

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

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

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

NIST/DOE Evaluation of PCS Options for IGFC Power Plants

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

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

2. Introduction

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

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

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

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

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

3. Markets For High Megawatt Power Converters

A. Current Markets

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

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

Specific examples of several of these applications include:

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

(Lai Slide 4)

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

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

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

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

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

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

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

(Hingorani Slide 17)

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

B. Future Commercial Markets

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

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

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

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

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

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

A number of potential approaches to resolving these issues include:

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

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

C. Future DOD Markets

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

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

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

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

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

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

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

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

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

4. Integration of Workshop Presentation Information

A. New Approaches to System Design

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

Today

- Rule Based Design
- Standard Parts
- Increasing Complexity
- Specifications, Documents
- Small Samples Statistics

Tomorrow

- Relational Based Design
- Standard Processes
- Increasing Detail
- Model is the Specification
- Physics Based Analysis
- Statistics from All of Industry

(Ericsen Slide 2)

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

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

(Ericsen Slides 19, 20 and 21)

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

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

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

(Hingorani Slide 22)

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

B. New Topologies

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

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

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

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

(Enjeti Slide 30)

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

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

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

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

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

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

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

The advantages and disadvantages of this system are summarized below:

Advantages	**Disadvantages**

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

(Ozpineci Slide 4)

Other attributes include

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

(Ozpineci Slide 6)

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

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

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

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

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

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

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

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

(Reass I Slide 16)

C. New Materials

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

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

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

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

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

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

(Mazumder Slide 2, presentation not provided)

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

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

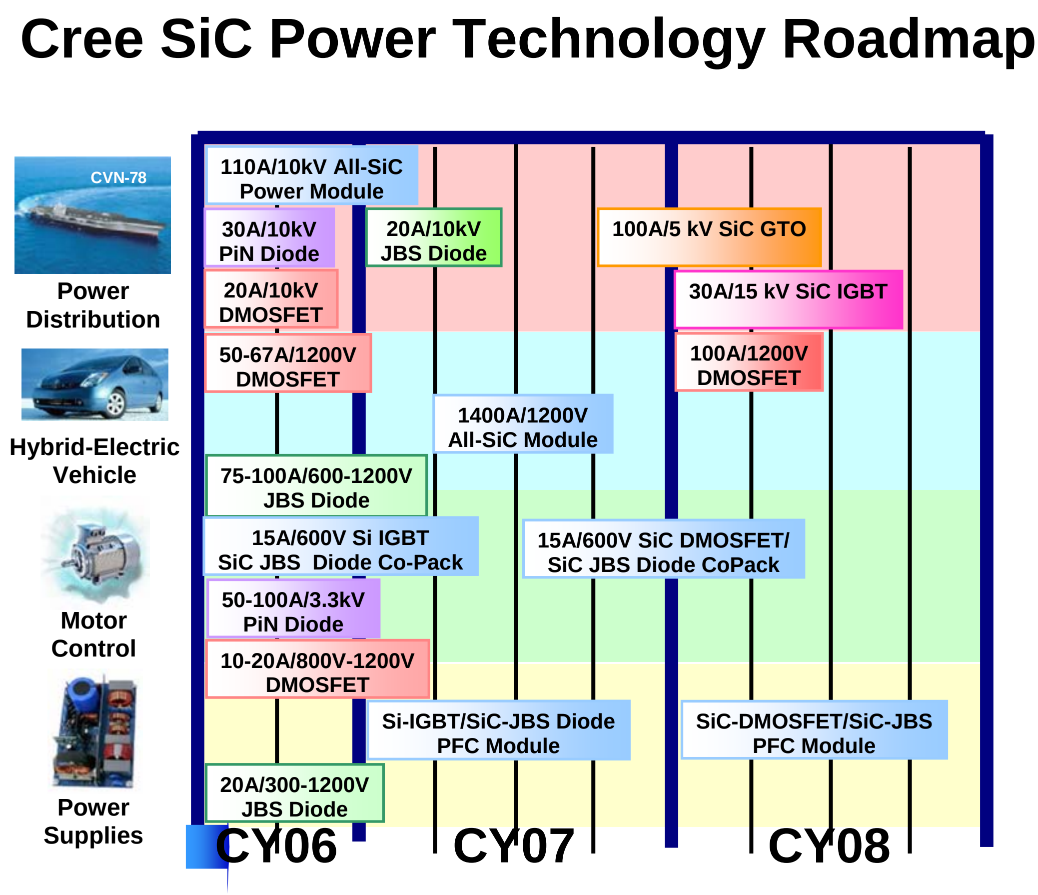
(Grider Slide 3)

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

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

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

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



(Grider Slide 32)

D. New Components

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

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

(Hingorani Slide 18)

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

i. Inverters

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

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

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

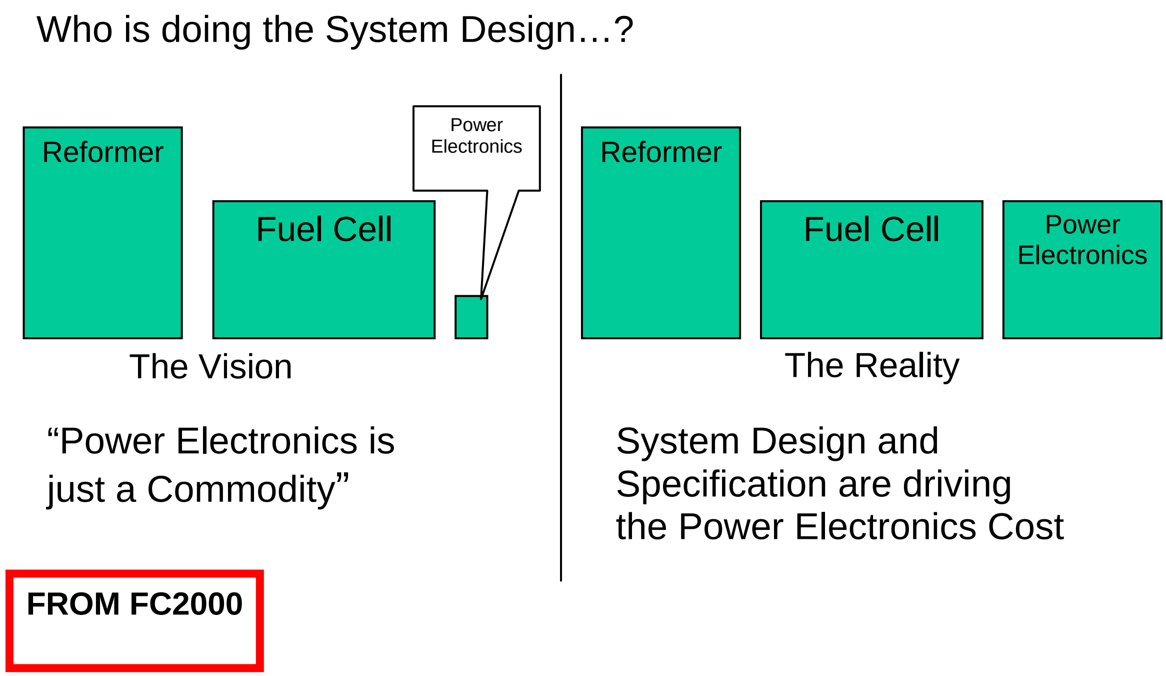
(Casey)

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

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

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

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



(Casey)

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

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

(Staines I Slide 3)

ii. Transformers

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

The following conclusions apply to this system:

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

(Reass II Slide 23)

iii. Capacitors

Film capacitors are commonly used for Power Conversion:

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

(Staines II Slide 2)

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

Improvements in capacitor capability could impact converter costs as follows:

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

(Staines II Slide 6)

iv. Integrated Devices

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

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

(Leslie Slide 2)

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

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

Further assembly of subsystems onto the chip could include:

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

(Leslie Slide 18)

5. Grid Connection Issues

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

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

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

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

6. IGFC Systems

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

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

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

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

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

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

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

Any PCS topology selected:

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

(Gordon Slide 8)

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

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

(Gordon Slide 19)

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

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

The approach and boundary conditions being used for this study are described below:

- Methodology for impact study:
  - Classify power converter architectures and component technologies that may reduce cost
  - Perform tabular calculations of cost for each option using estimated advantages of new technologies
  - Use component modeling, and circuit and system simulations to verify and refine calculations
- Consider power electronics and/or transformer up to 18kVAC, and assume transformer from 18 kVAC to transmission level voltage
- Boundary conditions and performance parameters:
  - FC Stack: center tap ~700 VDC, 1000 A
  - Individual FC stack current control (may be necessary for FC reliability)
  - Fault tolerant and serviceable
- Converter cost components:
  - Semiconductors
  - Module Packaging
  - Cooling System
  - Magnetics: Filter Inductors and HF voltage isolation transformers
  - Transformer up to 18kV
  - Breakers

(Hefner I Slide 5 and 6)

The initial baseline for the study is a center tapped fuel cell (approximately 700 VDC 0.6 MW) with a DCDC current regulator, a 480 VAC inverter, and 60 Hz transformers to raise the output voltage to 18 kVAC. This option is chosen as the baseline because it includes the individual functions necessary to expand to a DC common bus, and to high-voltage and/or high-power inverter topologies. The “present lowest-cost” option combines the DCDC regulator and 480 VAC inverter functions into a single converter stage that uses the “present lowest-cost” switching power device, a 1200 V IGBT module.
(Hefner I Slide 8)

For the low voltage inverter options, advanced semiconductor technologies such as SiC power devices enable the use of higher frequencies that may reduce the cost of passive components. The advanced semiconductor devices may also result in lower switching losses resulting in higher power conversion efficiency and lower cost thermal management systems. SiC power semiconductor devices have recently begun to emerge as commercial products where low current SiC Schottky diodes are becoming common place in computer server power-factor-correction circuits. 1200 V SiC MOSFET switches and 1200 V hybrid SiC-Schottky/Silicon-IGBT modules are also expected in the near future.
(Hefner I Slide 10)

The second class of power converters being evaluated uses a DCDC converter to step the voltage up to 6 kV and a medium-voltage inverter is used to produce 4160 VAC, then a transformer is used to raise the voltage to 18 kVAC. In this case, the DCDC converter can combine the function of increasing voltage with the function of regulating fuel cell current. The advantage of using a medium-voltage inverter is that it reduces the current for a given power processing level so that a single inverter can be used for multiple fuel cell stacks.
(Hefner I Slide 11)

Various semiconductor options exist for medium-voltage inverters including HV-IGBTs, IGCTs, and high-voltage SiC devices. Recently, commercial HV-IGBT modules have been introduced to increase the voltage and current level to 6.5 kV, 600A, and commercial 6.5 kV, 3000 A IGCT's have been introduced that provide improved GTO switching speed using a high current, low-inductance gate drive to switch-off the full wafer GTO in unity-gain mode. However, these existing semiconductor devices require the use of multi-level inverters for medium voltage applications. This is due to the lack of voltage margin when using a 6.5 kV switch and, also, to the relatively low switching frequency of the high voltage Silicon devices (<1 kHz). On the other hand, the high-voltage, high-frequency (10 kV, 20 kHz) SiC semiconductor devices currently under development by the DARPA HPE program would enable the use of a single level inverter with a much lower part count and lower filter inductance requirements.
(Hefner I Slide 12 and 13)

Finally, various power converter architecture options are being evaluated for using a single medium-voltage, high-power inverter for multiple 700 V, 0.6 MW fuel cell stacks. Each architecture option imposes different requirements on the DCDC converter and DCAC inverter functions and thus realizes different benefits from advanced semiconductors, magnetics, and capacitors. For example, architectures requiring DCDC converters with high voltage-gain or voltage-isolation may also benefit from advanced magnetic materials, which, in effect, step-up the voltage using the high-frequency magnetic components rather than a much larger 60 Hz transformer. In each case, the power converter architecture and component technologies must be considered together to determine the overall benefits to the PCS system and to identify a complete set of advanced technologies required for a given approach.
(Hefner I Slide 14 and 15)

After the briefing on the approach being considered for the impact study and on the individual power converter technologies, the workshop participants were asked during an open discussion session to provide feedback on additional specifications and technologies to be aware of in the study. The questions posed during this session and the consensus for additional considerations to the impact study are summarized below.

Requested inputs from the Workshop participants:

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

(Hefner II Slide 2)

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

- Specifications for filter requirements
    - Inverter harmonics requirement –IEEE 519
    - EMI requirements – Mil STD 461 or equivalent
- Specifications for FC DC regulator
    - Ripple requirement - <3% for frequencies < 1kHz
- Year 2020 FC may be 2000 V (center-tap)

(Hefner II Slide 3)

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

8. Formation of Roadmap Committee

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

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

Consensus 1: Yes

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

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

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

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

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

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

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

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

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

9. List of Workshop Presentations

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

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

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

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

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

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

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

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

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

Hingorani
High-Megawatt Converter Technology Workshop

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

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

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

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

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

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

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

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

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

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

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

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

10. Appendices

Appendix A. Workshop Agenda

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

Appendix B. List of Workshop Participants

Name	Affiliation	Email	Telephone
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Sam Biondo	DOE-Fossil Energy	samuel.biondo@hq.doe.gov	301-903-5910
Leo Casey	Satcon	leo.casey@satcon.com	617-897-2435
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Ron Wolk	Wolk Integrated Technical Services (WITS)	ronwolk@aol.com	408-996-7811

Invited Participants Who Were Unable to Attend

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Thomas Lipo	U. of Wisconsin at Madison	lipo@engr.wisc.edu	608-262-0287
John Pazik	Office of Naval Research	pazikj@onr.navy.mil.	
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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.

Presentations

Keynote

Biondo

High-Megawatt Converter Technology Workshop

Sam Biondo

January 24, 2007
National Institute of Standards and Technology

RECALL THE INVITATION TO THIS MEETING STATES:

"[It] 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"

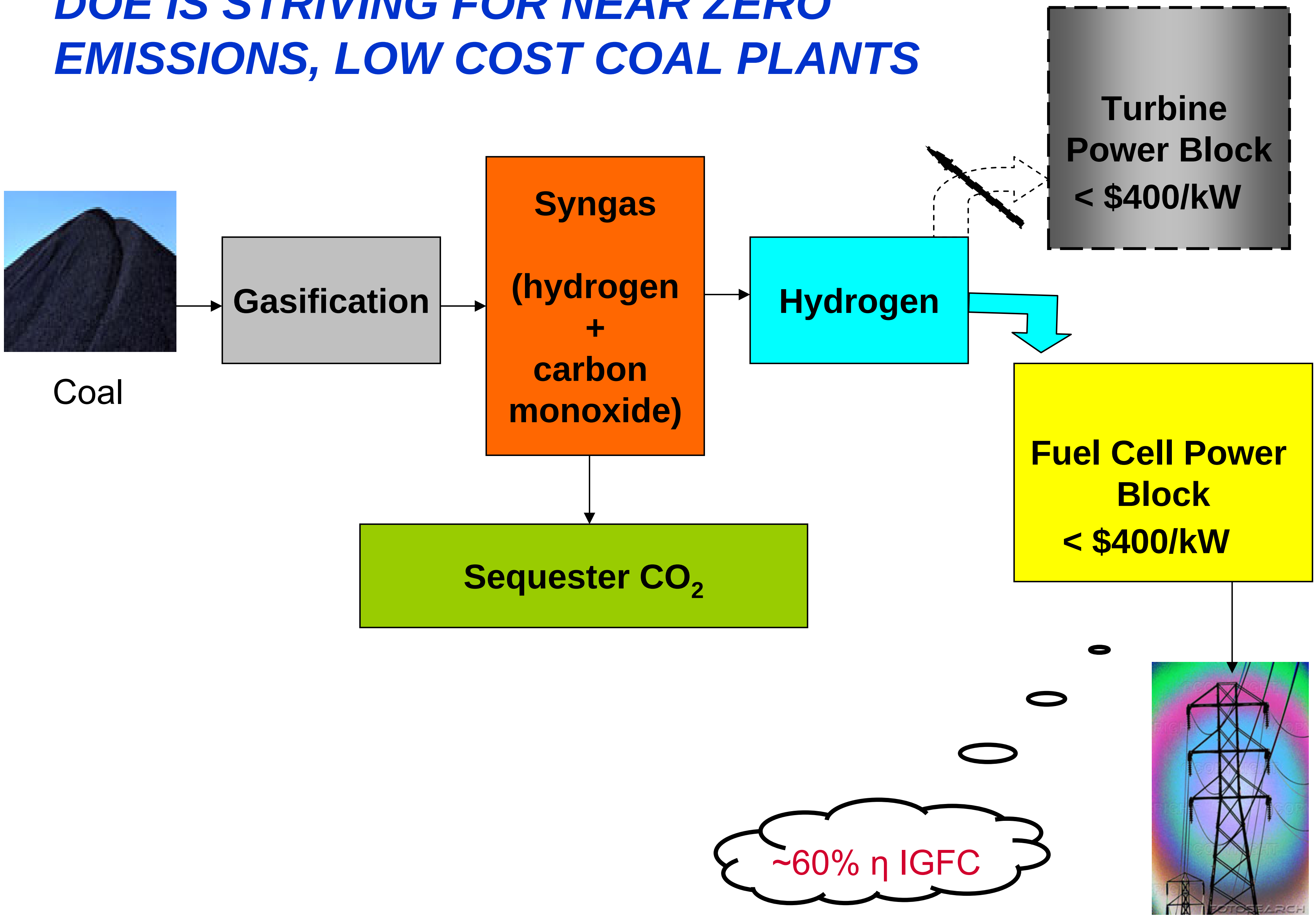
I WANT TO BRIEFLY SHARE SOME

BACKGROUND INFORMATION

The Three Horsemen of the Energy R&D Apocalypse: pollution, high cost, low efficiency

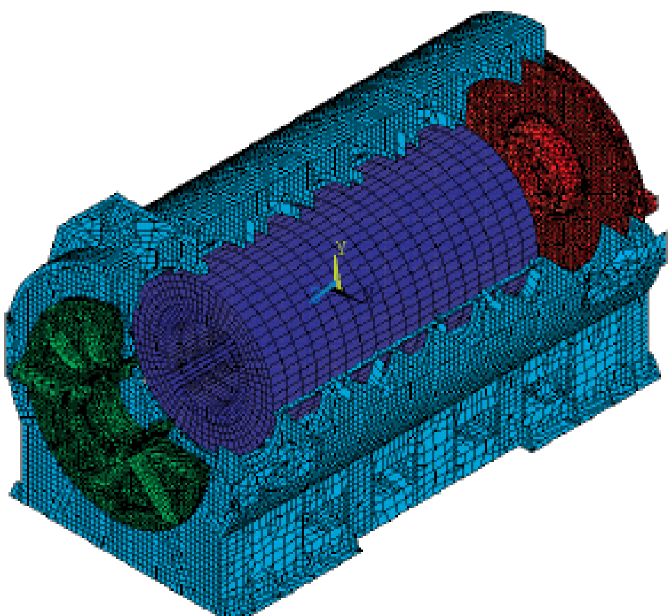
Cropped from painting by Victor Mikhailovich Vasnetsov

DOE IS STRIVING FOR NEAR ZERO EMISSIONS, LOW COST COAL PLANTS



Turbine systems are the right size and inexpensive

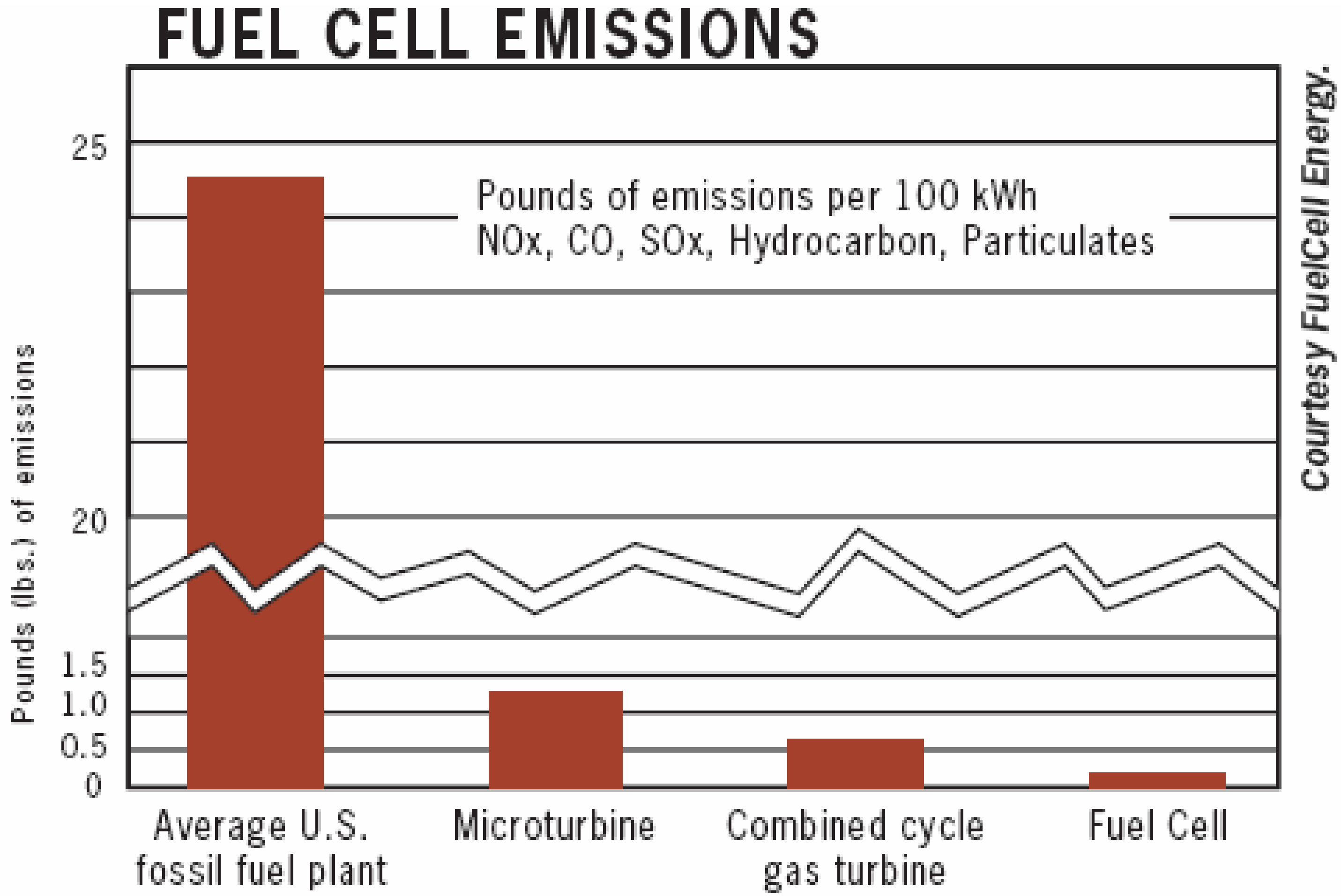
< $400/kW



	7FH2 Model 741 / 743 ‡
Cooling	Hydrogen directly cooled rotor and conventionally cooled stator
Configuration	Single-end drive, end shield mounted
Rated Speed	3600 rpm/60 Hz
Output	195.5 MW/60 Hz
Power Factor	0.85 lag
MVA Rating	230 MVA/60 Hz
Terminal Voltage	18 kV
Temperature Rises	Allowable Class B per IEC/50 Hz And ANSI/60 Hz Standards
Insulation Class	Rotor - Class F; Stator - Better than Class F
Excitation System	Bus Fed, Static Excitation

‡ Note: Could be **W501G, with 1S.W501G**

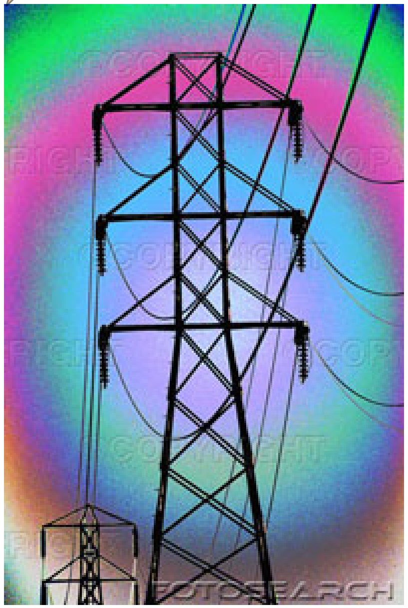
Fuel Cells are much cleaner but still relatively small and expensive



Efficiency Is Also Major Factor

Where did the 40% go?

Inspired by Mary Peters Fieser (1909–1997)



Line Losses Further Deplete Generation

- A typical loss factor of an ac overhead line is 4.4% per 100 miles at 345 kV.
- At 500 kV, the ac overhead losses are down to 2.5% per 100 miles.
- The losses for 400 kV dc overhead are lower than 1% per 100 miles‡.

- So further reducing generation losses will help offset foot-warming losses.

‡From Advanced Power Transmission of the Future, Mario Rabinowitz
Armor Research, 715 Lakemead Way, Redwood City, CA 94062-3922
Mario715@earthlink.net

Wants/Needs In Re: Theory of the Government's Role

- Needs are set by future turbine (7FB or W501G type) power block's expected low costs and high performance.
- Wants will depend on the stretch goals

  -purpose of stretch goals is to inspire efforts to go well beyond what is currently feasible; such goals are only achievable if they stimulate and inspire creativity, invention and innovation.
- Stretch goal are not just desirable, they are needed to justify government funding.

Theory of the Government's Role

- Megawatt scale fuel cell power conditioning technology is needed
  - -at very low cost; perhaps as low as $40/kW
  - -at very high efficiency; likely >98%
  - -and perhaps better than today's (e.g.,7FH2/1S.W501G) demonstrated high availability

Theory of the Government's Role

- Need to understand what economists call "spillovers" and the concept of "market failures."
- (Note: *Check out e.g., web articles on foreign direct investments (FDI) and spillovers in electronics in various countries, e.g., U.K., Taiwan, Baltics, etc*…)

Spillovers

From the firm's perspective, the firm invests in R&D until the expected risk-adjusted private returns of the last research project equals its costs.

Average returns to R&D to the firm are high— 20 to 30 percent, on average[1]— but the returns to society are even higher— often 50 percent or more.

These R&D "spillovers" occur as others use research results and extend them in directions the original innovator often could not have imagined.

The result of spillovers is that an innovator is compensated for only a fraction of the total returns.

Stiglitz (Nobel Prize in Economics in 2001) said,

***"Market failures" cause firms acting in their own best interests to under-invest in R&D from society's perspective*.**

Under-investment occurs because firms cannot appropriate all the returns ["spillovers"] to their R&D investments

And because capital market imperfections may make financing R&D more expensive [i.e. R&D cannot be collateralized] than other investments.

Much of government direct R&D funding goes to **applied research and development** in industry,

Traditionally, most of this funding has been to satisfy directly government objectives like space, defense, health research, environment, energy, transportation, agriculture, etc.

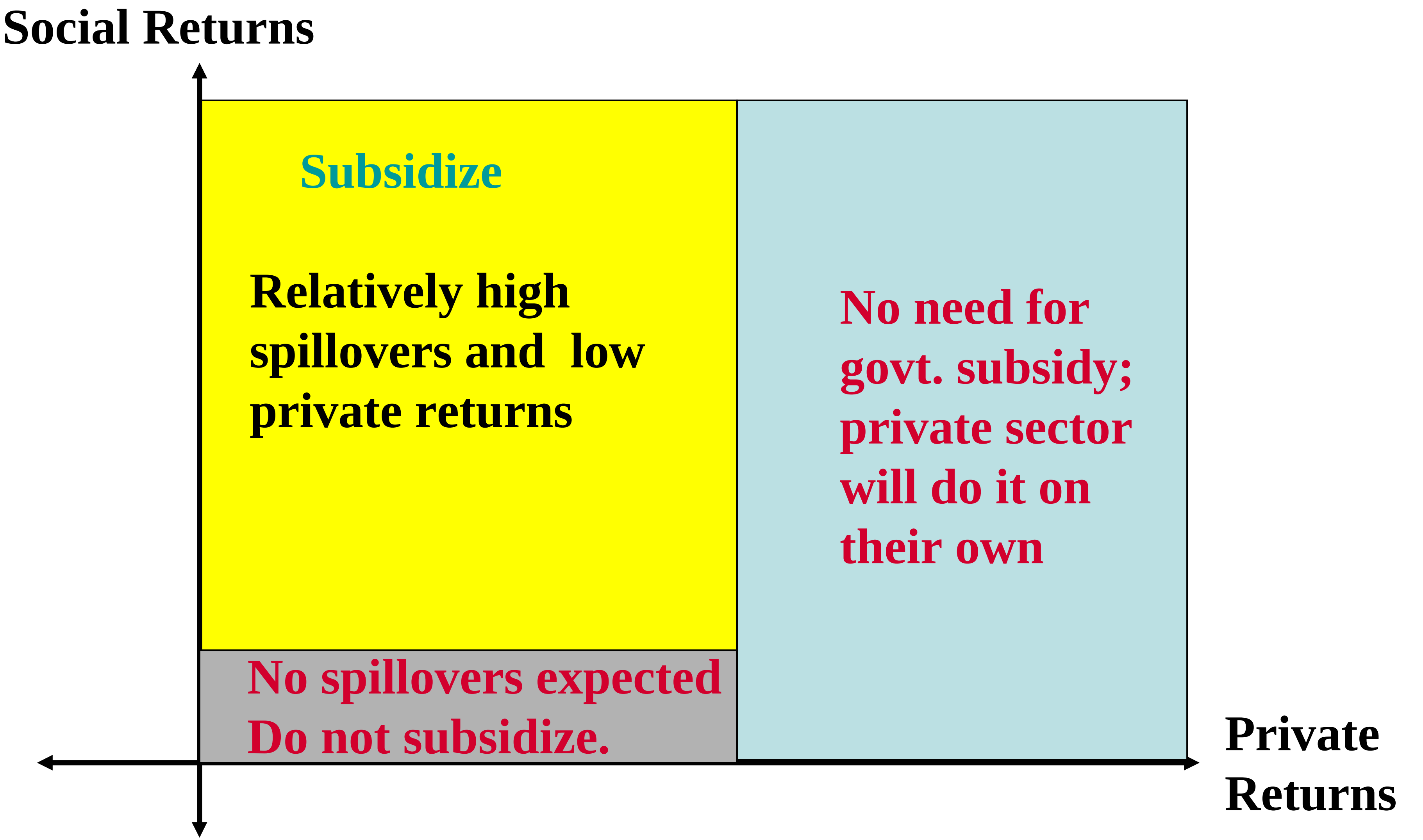
While the “market failures” may be less extreme in applied research and development than in basic research, they still exist.

Even the most applied R&D is inherently risky and can generate large “spillovers.”

The rationale for government intervention is not that the government is better than the private sector at picking winners, but that there exist important spillovers ***even for applied technology*.**

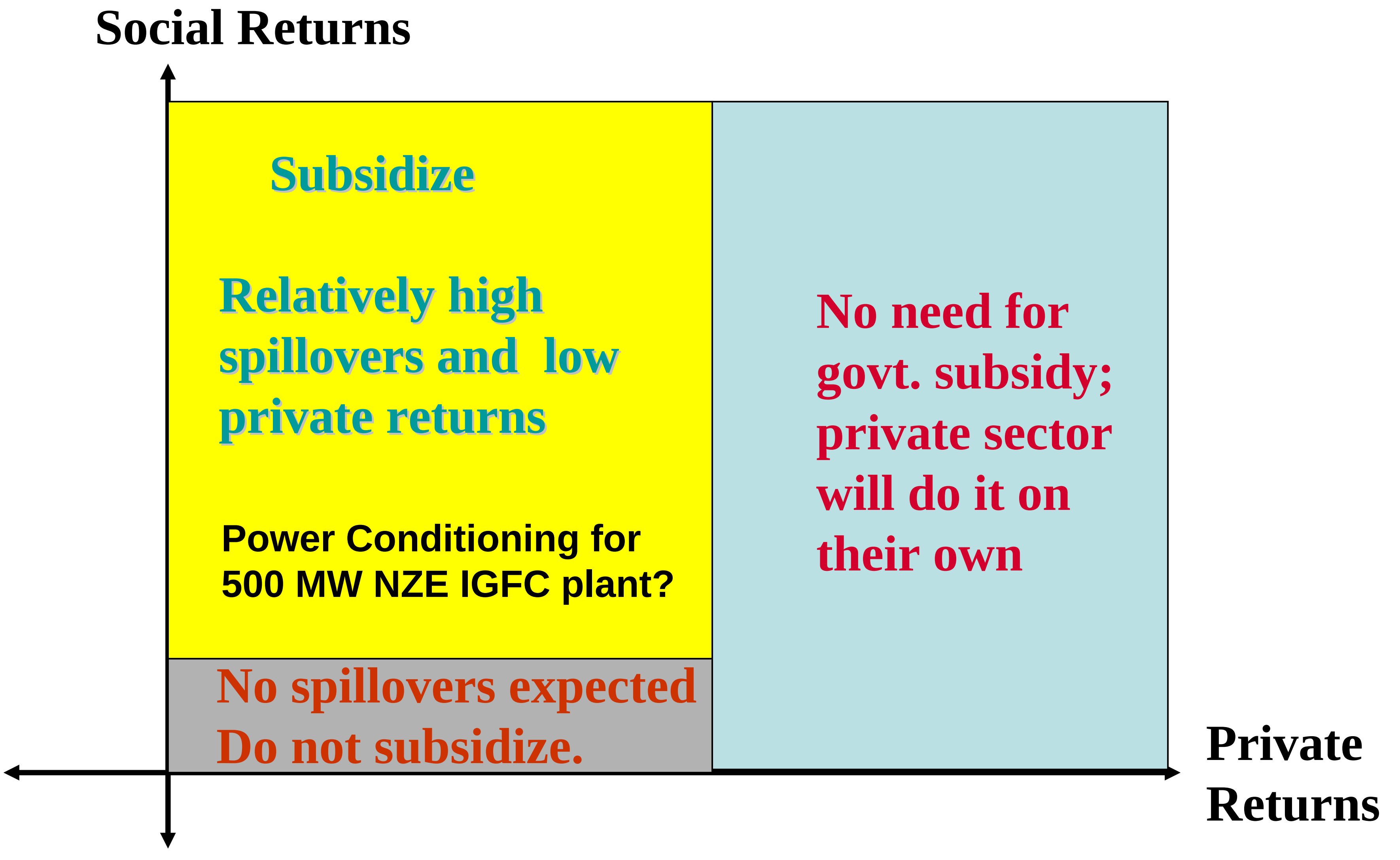
The objective of the government is thus to identify winning projects that would be privately unprofitable but socially beneficial because of high spillovers.

Candidates for Subsidies: Expected Social v Private Returns



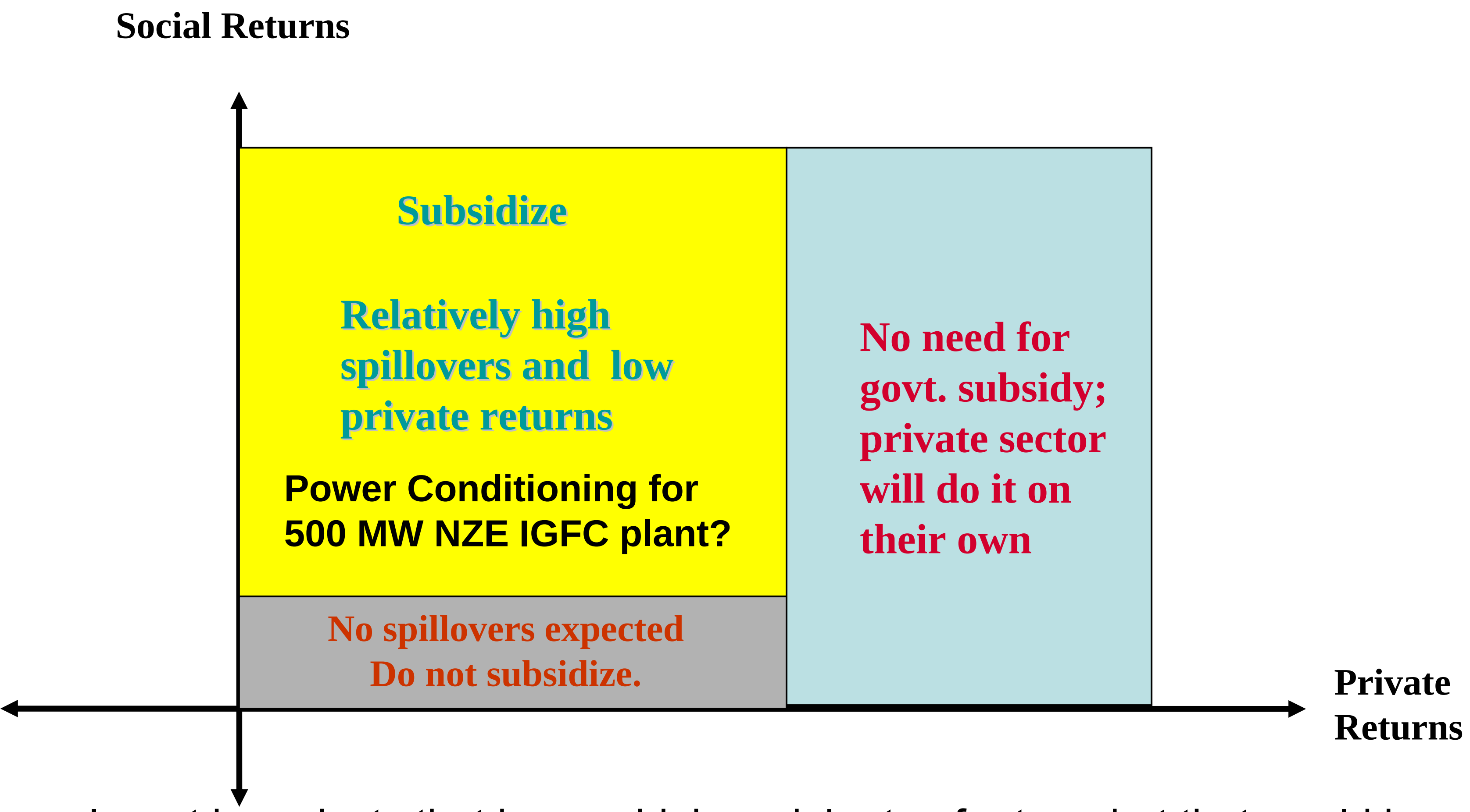
(adapted from Stiglitz and Wallsten: Public-Private Technology Partnerships: Promises and Pitfalls)

Candidates for Subsidies: Expected Social v Private Returns



(adapted from Stiglitz and Wallsten: Public-Private Technology Partnerships: Promises and Pitfalls)

R&D spillovers are “positive externalities.”



•Invest in projects that have a high social rate of return, but that would be underfunded, delayed or otherwise inadequately pursued in the absence of government support.

•Pursue projects for which the gap between the social and private rates of return ("the spillover gap") is large.

Tangible Benefits of Private/Public Collaboration

- Value of derivatives should provide incentives for both public and private organizations, and
- Collaboration would enable leveraging resources

Why does DOE care about these issues now?

- There are no current market incentives to develop power conditioning systems for multi-hundred megawatt fuel cells systems and to achieve stretch goals for cost, efficiency, and reliability.

- Such PCS systems would lead to substantial public benefits. The potential spillover gap is large.

The Three Horsemen of the R&D Finance Apocalypse: the time value of money; the risk of technical failure; and the cost of the R&D program itself.

Cropped from painting by Victor Mikhailovich Vasnetsov

Thank you for your attention

Session 1

Ericsen

Advanced Electric
Power Systems Thrust

Model-Based Specification and Simulation-Based Design and Procurement

Terry S Ericsen

“System of Systems” Design Challenges

Today

- Rule Based Design
- Standard Parts
- Increasing Complexity
- Specifications, Documents
- Small Samples Statistics

Tomorrow

- Relational Based Design
- Standard Processes
- Increasing Detail
- Model is the Specification
- Physics Based Analysis
- Statistics from All of Industry

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Complexity

(From “Modeling and Simulation in System Engineering: Whither Simulation Based Acquisition?” By Andrew P. Sage and Stephen R. Olson, George Mason University)

- The more identical that a model must be to the actual system to yield predictable results, the more complex the system is.
- Complex systems “...have emergence ... the behavior of a system is different from the aggregate behavior of the parts and knowledge of the behavior of the parts will not allow us to predict the behavior of the whole system.”
- “In systems that are ‘complex,’ structure and control emanate or grow from the bottom up.”
- A system may have an enormous number of parts, but if these parts “interact only in a known, designed, and structured fashion, the system is not complex, although it may be big.”
- Although a physical system maybe not be complex, if humans are a part of the system, it becomes complex

Example: The Electrical System and The Power Electronics Thesis

- Present electrical power systems are complex.
  - At equilibrium, 60Hz. Supplies power to 60Hz loads the system is stable and predictable.
  - If perturbed, the system can become unstable and unpredictable – bifurcation can occur.
  - Humans are needed to operate the system
- Future PEBB based power electronic systems will not be complex.
  - Automation is possible -- reduced operating costs
  - Progressive integration -- reduced system costs
  - Higher availability due to physics-based health prediction – reduced maintenance costs
  - Increased reliability and life by controlling overstresses
  - Increased applications and technologies

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New Technology Drivers

- ⇧ Power Density
- ⇧ Energy Density
- ⇧ System Efficiency
- ⇧ Control

- ⇩ Conversion Steps
- ⇩ Number of Phase Legs
- ⇧ Reconfiguration
- ⇧ Voltage
- ⇧ Current
- ⇧ Frequency

Source Voltage, rms Line-Line (volt)	***Estimated Device Blocking Voltage (volt)***	***Notes***
13,800	40,000	Many circuits are needed --parallel, series, and steps
4,160	12,000	Emerging solid-state solutions
440	1,300	Solid-state solutions available
115	350	

- Pulse forming networks require charging circuits ranging from **10kV to 40kV**.
- Pulse forming discharge circuits can require up to **100kV switching**.
- Modulator circuits require **10kV to 50kV** for input voltages and output voltages ranging from **50kV to 1MV**.

Ericsen, T., “Future Navy Application of Wide Bandgap Power Semiconductor Devices,” Proceedings of the IEEE, Vol. 90, NO. 6, June 2002, pp. 1077-1082.

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Power Systems Thrust

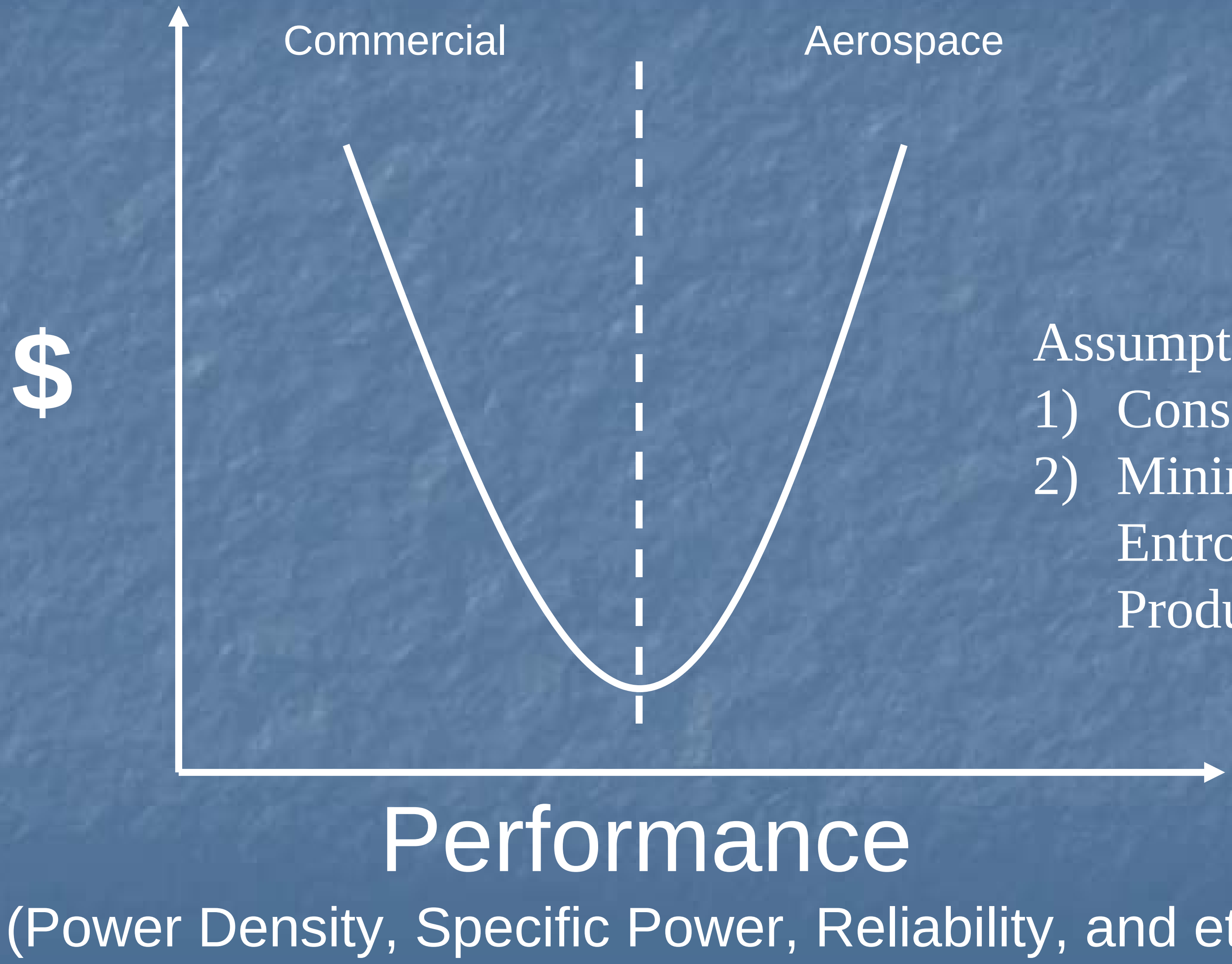
Level of Invention

by Michael S. Slocum
“Technical Maturity Using S-Curve Descriptors,” TRIZ Journal Archives,
http://www.triz-journal.com/archives/1998/12/a/

Level	Nature of Solution	Number of Trials or Variants Required to Find a Solution	Where Did The Solution Come From	Percentage of Patents in This Level
I	It was obvious!	A few	The designer’s narrow specialty field	~30%
II	Some modifications were made	Dozens	A single branch of technology	~55%
III	A radical change was made	Hundreds	Other branches of technology	<10%
IV	Solution is broadly applicable	Thousands to tens of thousands	From science – little known effects and phenomena of physics, chemistry and geometry	3-4%
V	A true discovery – previously unknown	Hundreds of thousands to millions	Beyond limits of contemporary science	< 1%

Advanced Electric Power Systems Thrust

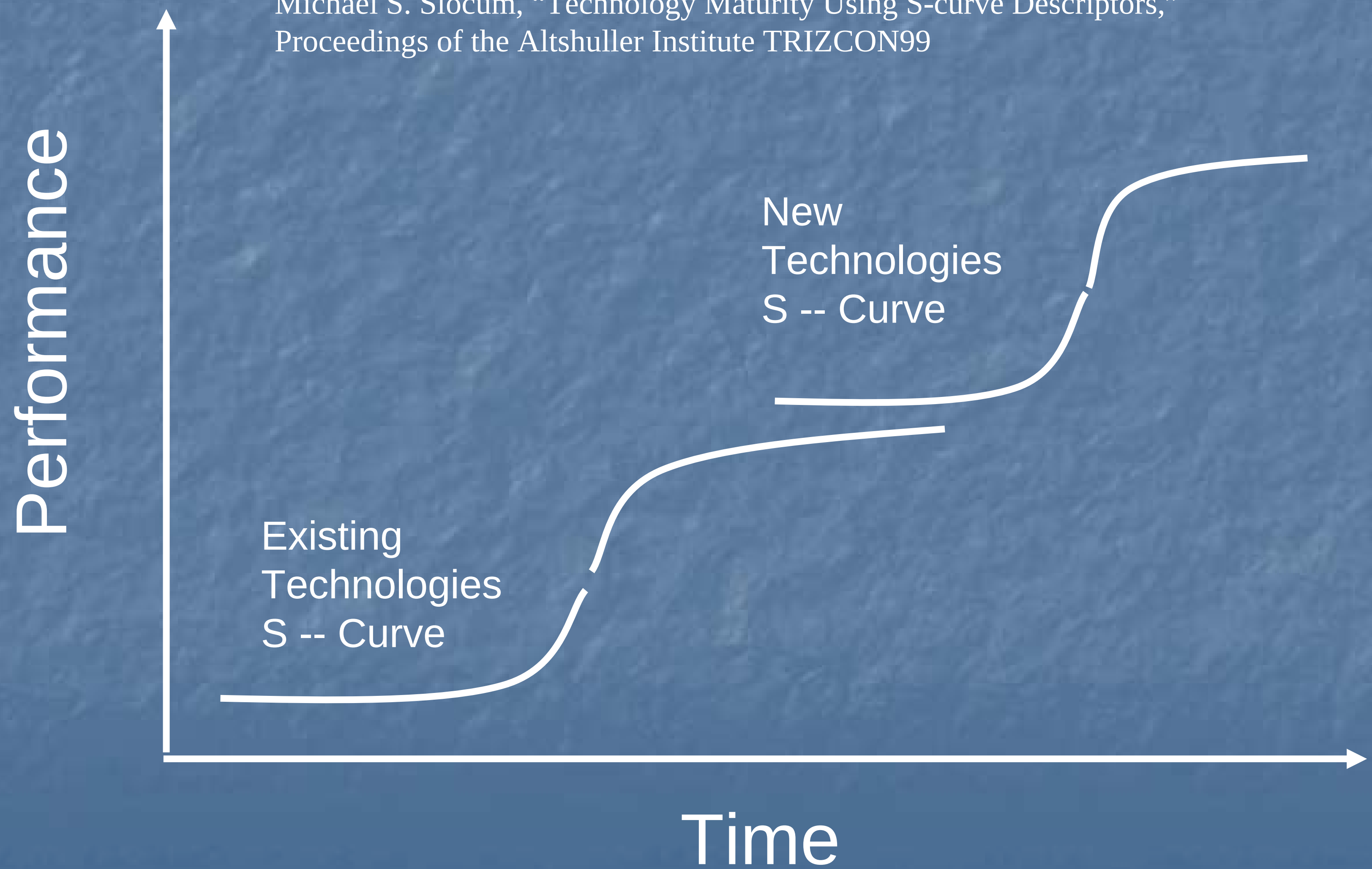
Development Processes



Assumptions:
1) Conservative
2) Minimum Entropy Production

Technology Maturity Based on the Micro-Evolution of Biological Systems

Michael S. Slocum, “Technology Maturity Using S-curve Descriptors,” Proceedings of the Altshuller Institute TRIZCON99



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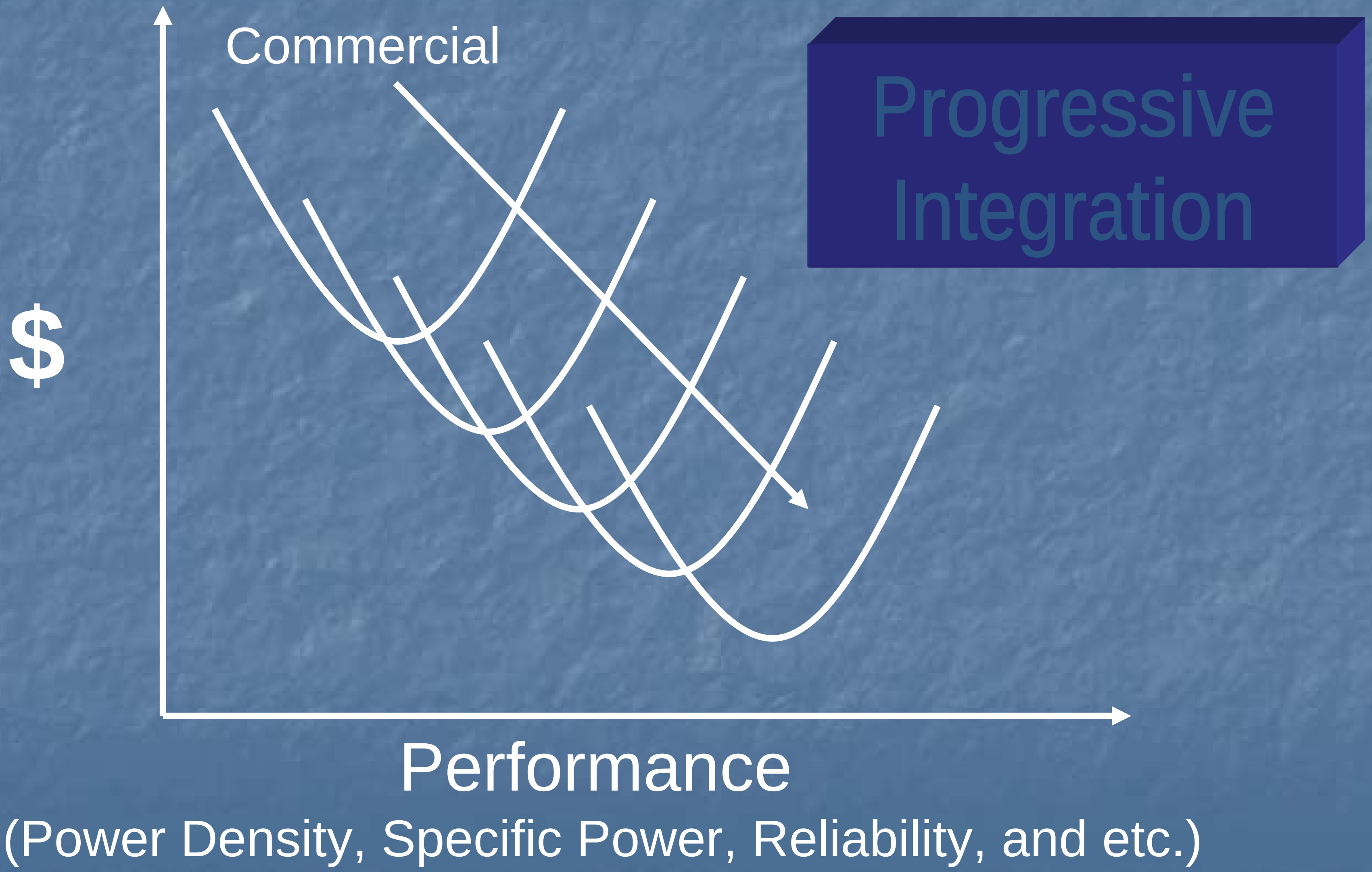
Development Process Continuum



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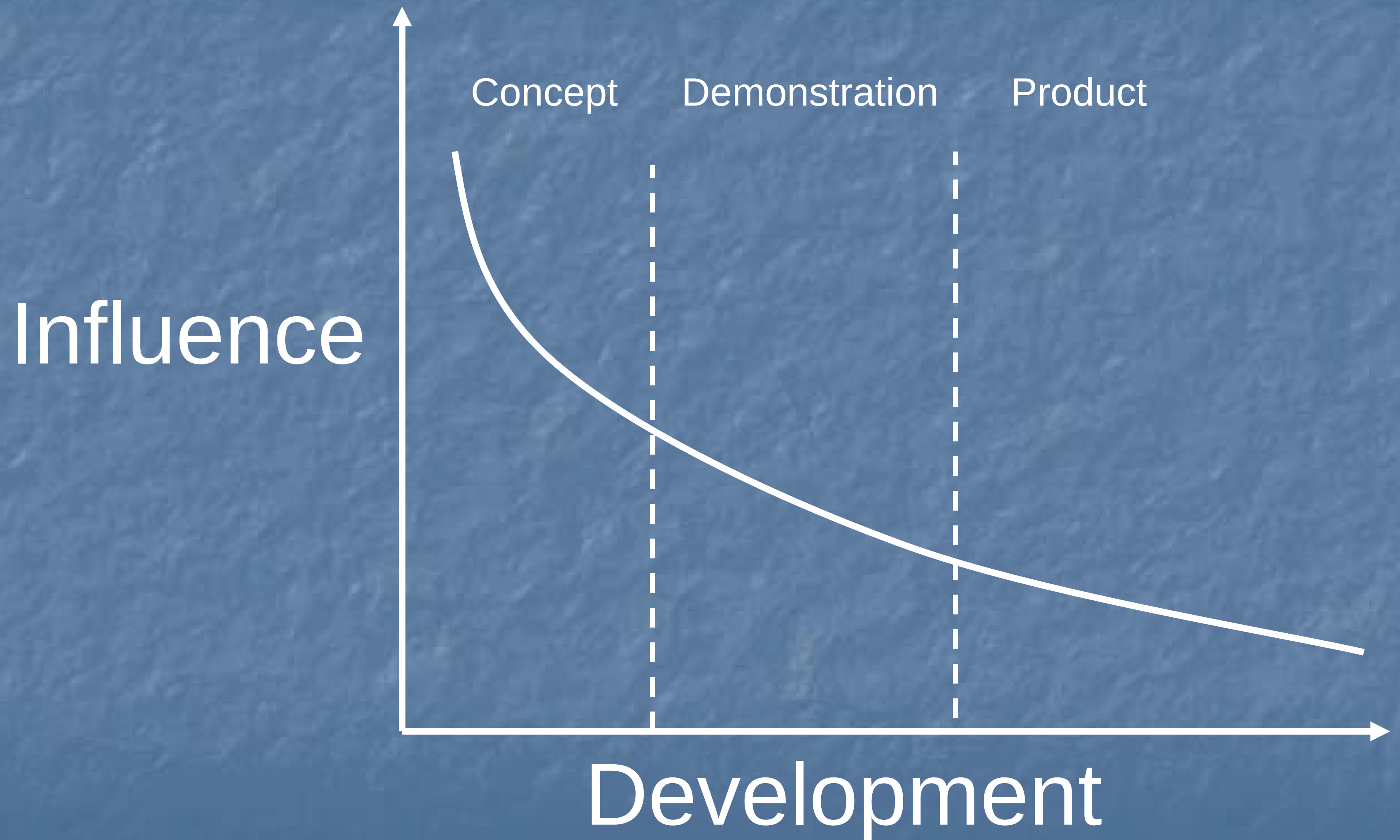
Management Influences



Modeling and Simulation as Early as Possible in a Project

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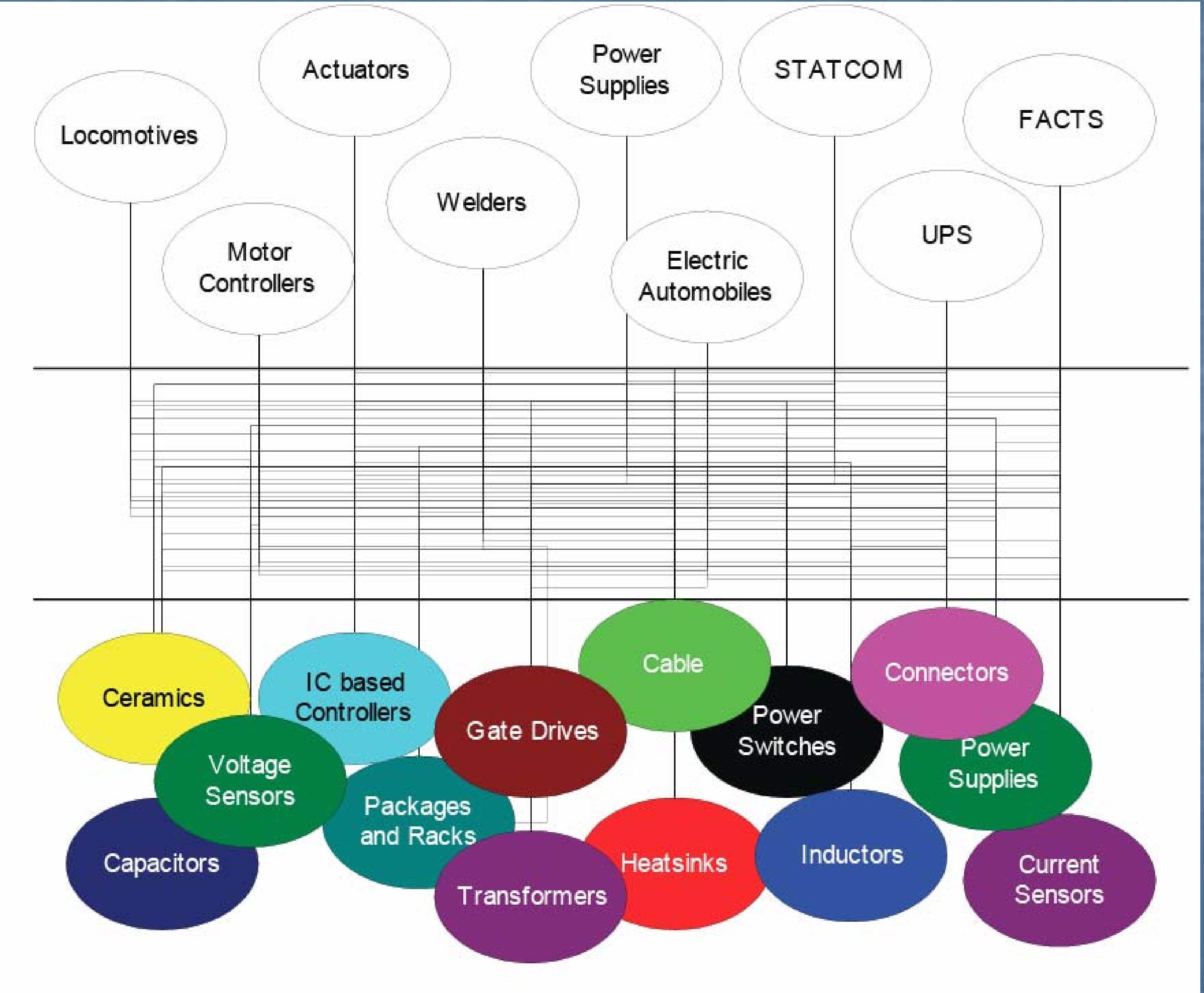
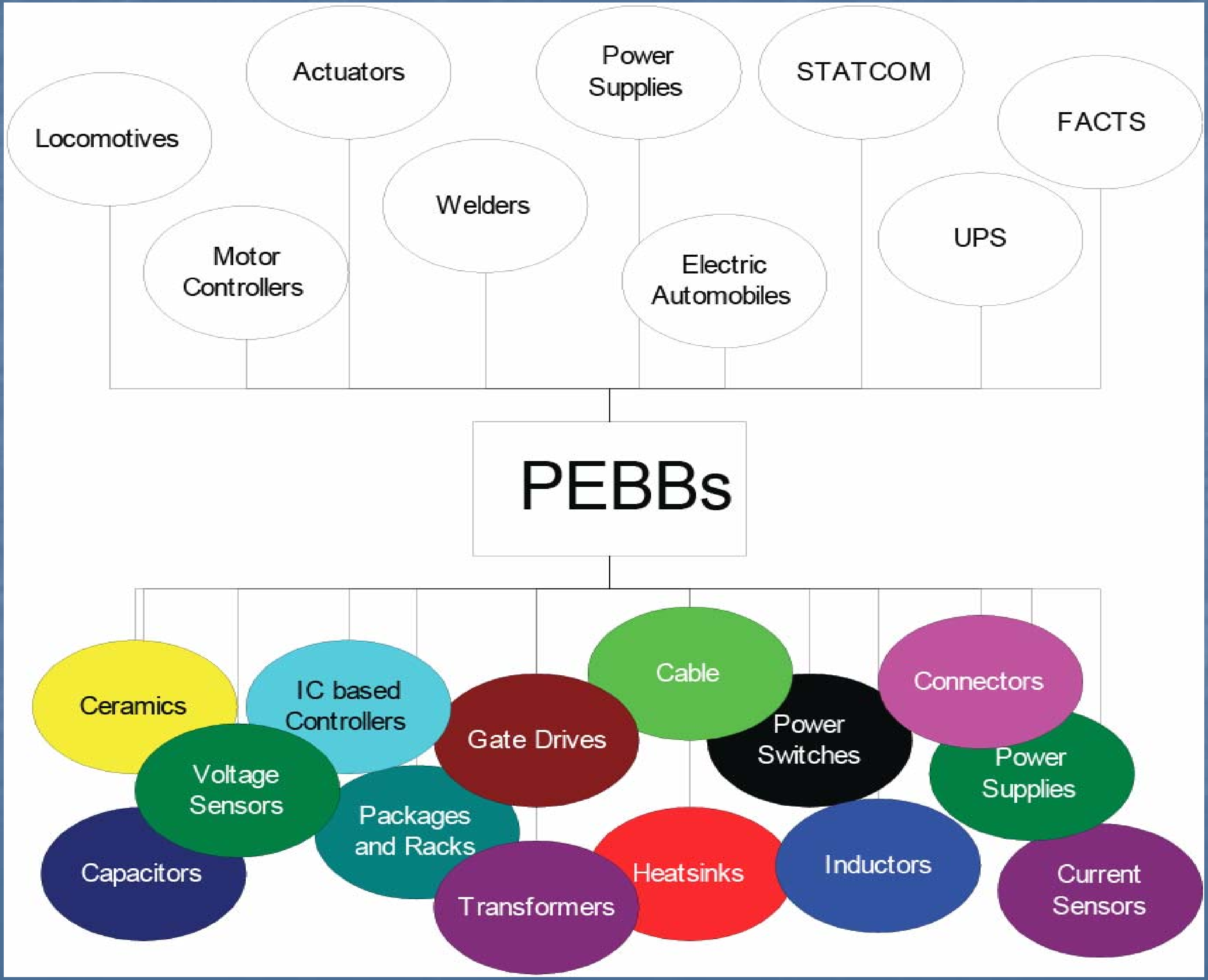
Traditional Power Electronics Industry



PEBB Based Power Electronics Industry



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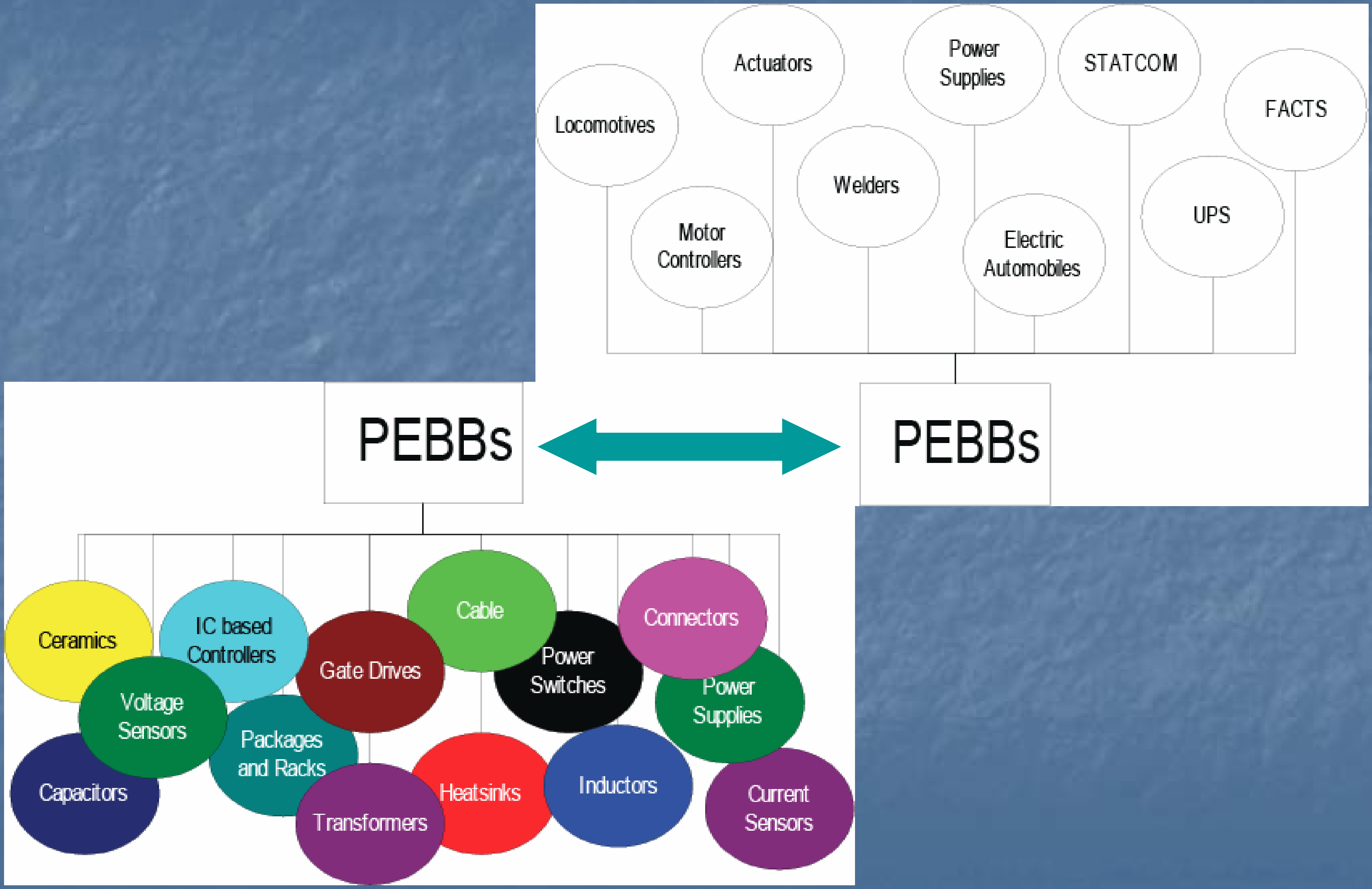
Asynchronous Processes for Multiplicative Product Development -- Concurrent Engineering



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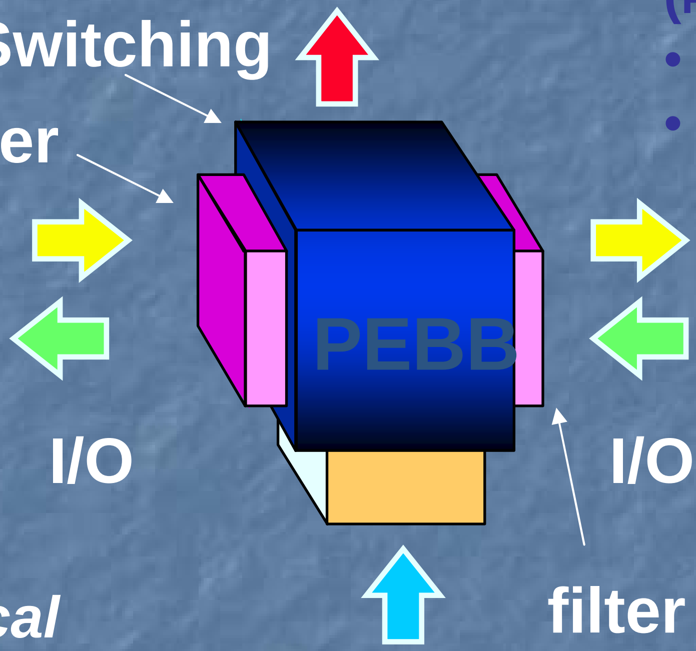
PEBB -- A Simple Set of Blocks for Power System Development (Functional)

- **PEBB defined by IEEE (Power Engineering Society)**
- **WG I8**
- **TF2, PEBB Technologies**



Senses what they are plugged into...

Senses what is plugged into them...

Makes the electrical conversion needed via software programming

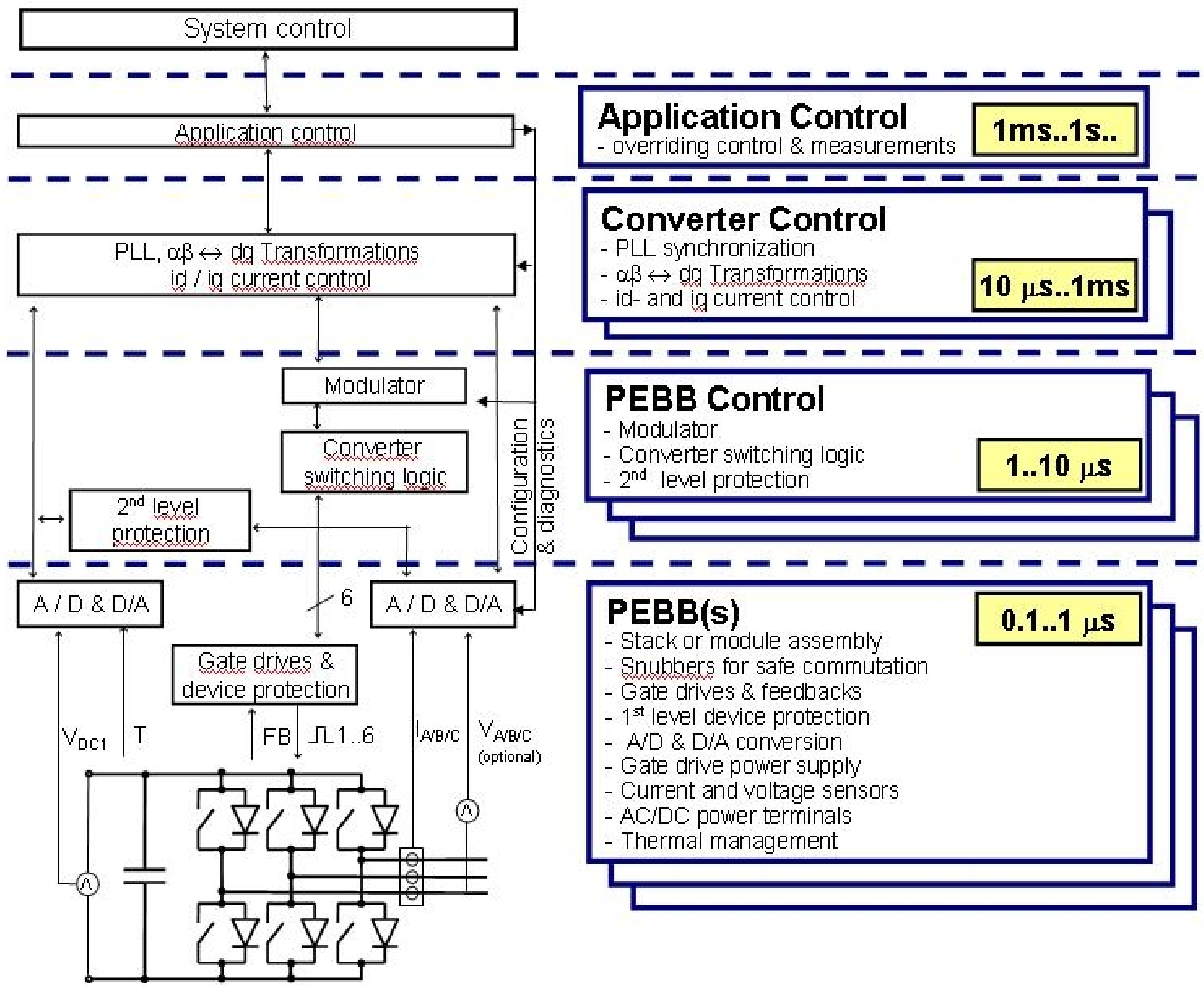
Functions In Software
Inverter
Breakers
Frequency Converter
Motor Controller
Power Supply
Actuator Controller

Industry Standards Initiated

Advanced Electric Power Systems Thrust

Universal Control Architecture for Control Interfaces (temporal) , IEEE Guide Initiated

PEBB Concept for Power Electronics



The Changing Role of Simulation

- **<u>Today,</u>** simulation is used for evaluation -- **Analysis**.
  - Simulation programs require detailed design information
    - Circuit parameters are entered before simulation begins.
    - Variations in design can be analyzed
- **<u>Tomorrow,</u>** simulation will become part of the design process -- **Synthesis**.

The Model Will Be The Specification

Future Design Process

Today

Tomorrow

The Design Cycle

Physics-Based Models are Required

- Product models must be specific
- Requirement models can be general
  - In fact, requirement models with very specific details, in the design phase, can lead to an overly constrained problem.

Validation, Emulation, and Incremental Prototyping

- Validation of models
  - Controller In the Loop
  - Processor In the Loop
  - Hardware In the Loop
- Real-time simulation is needed for real hardware
- High speed real-time simulation is need for high-speed controllers
- Multi-rate simulation for distributed simulation environments

Needs

- Modeling Standards
- Benchmark Models
- Public Library of Models
- A body of international volunteer experts for all of the above
- And ...

Vehicle System Power Problem

$$p = \varepsilon \frac{dw}{dt}$$

w = energy which is equal to the ceiling amount of the installed generation capacity (may increase over time with technology – fractionally)

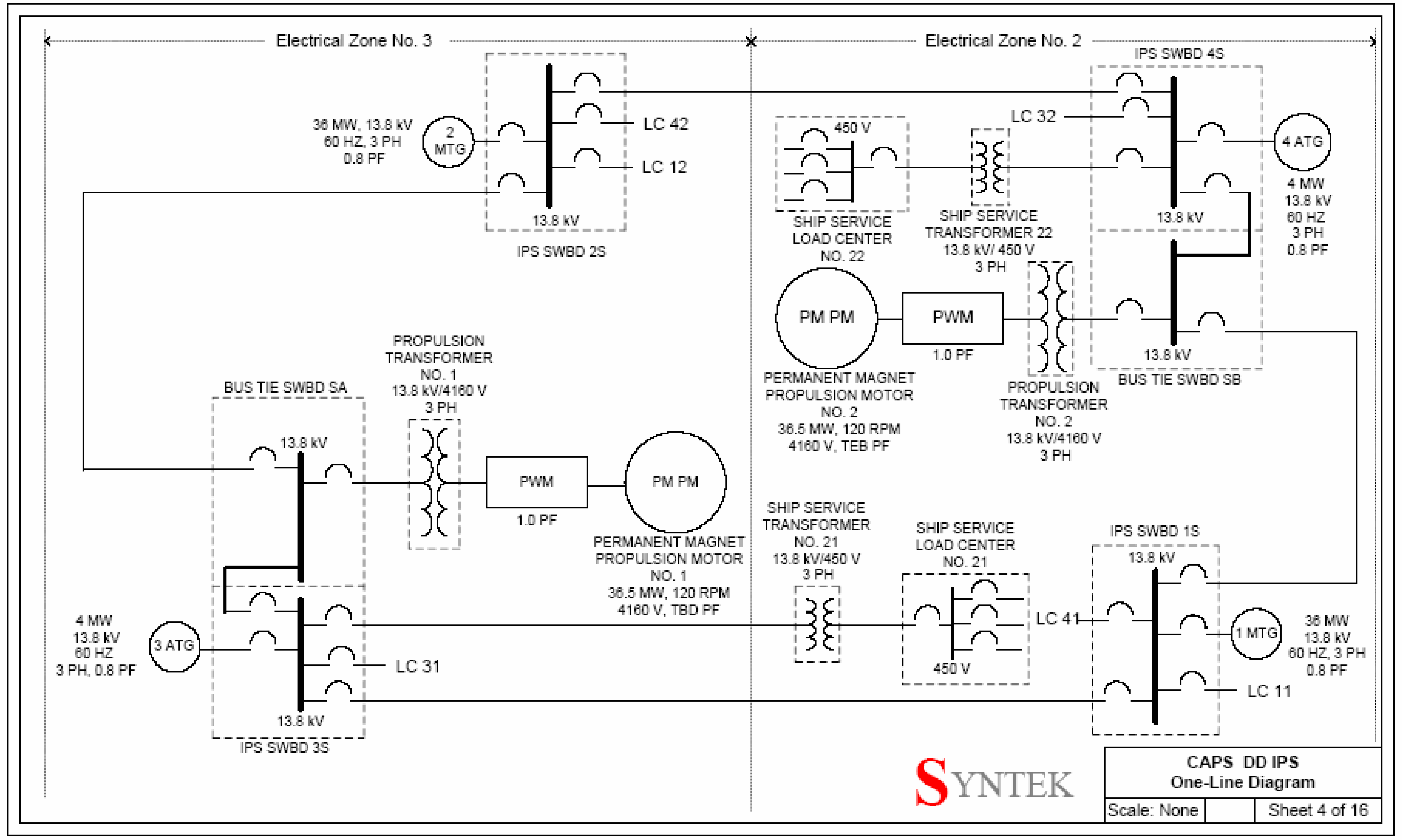
p, power requirements are increasing multiplicatively by 10x to 100x

ε = efficiency

Conditions:

1) Size, weight, cost stay the same or decrease
2) Open architecture, plug and play

Notional Integrated Power System (IPS)



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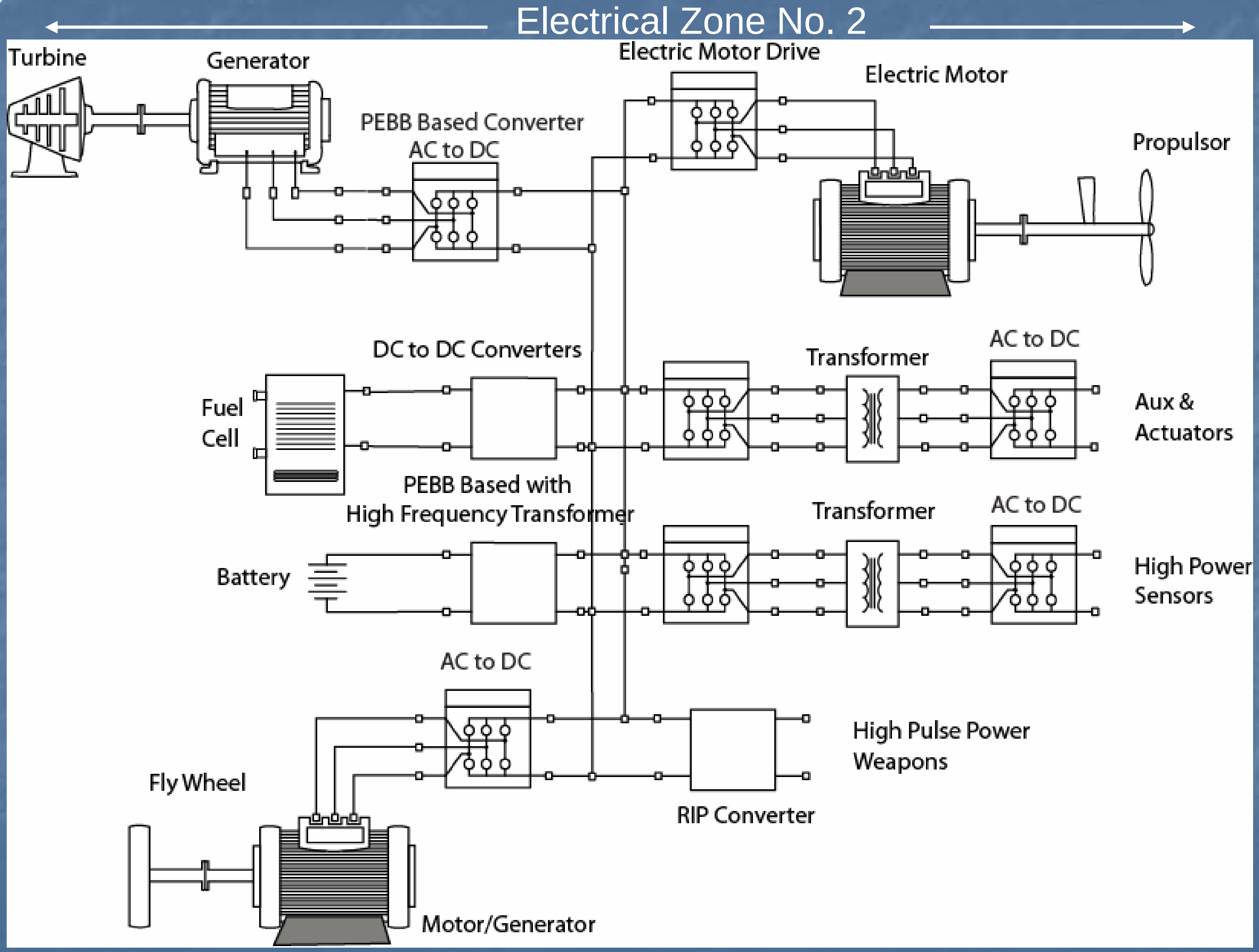
Architectural Transformation

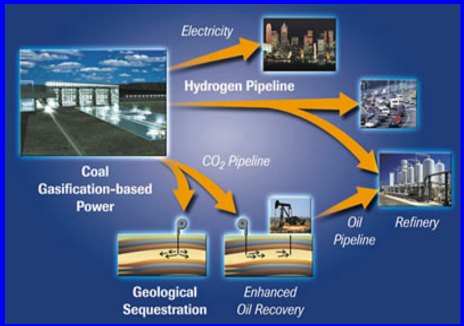


Session 1
Holcomb

DoD / Army Stationary Power Requirements

Secure, Reliable, Efficient Energy

Home Station to Foxhole





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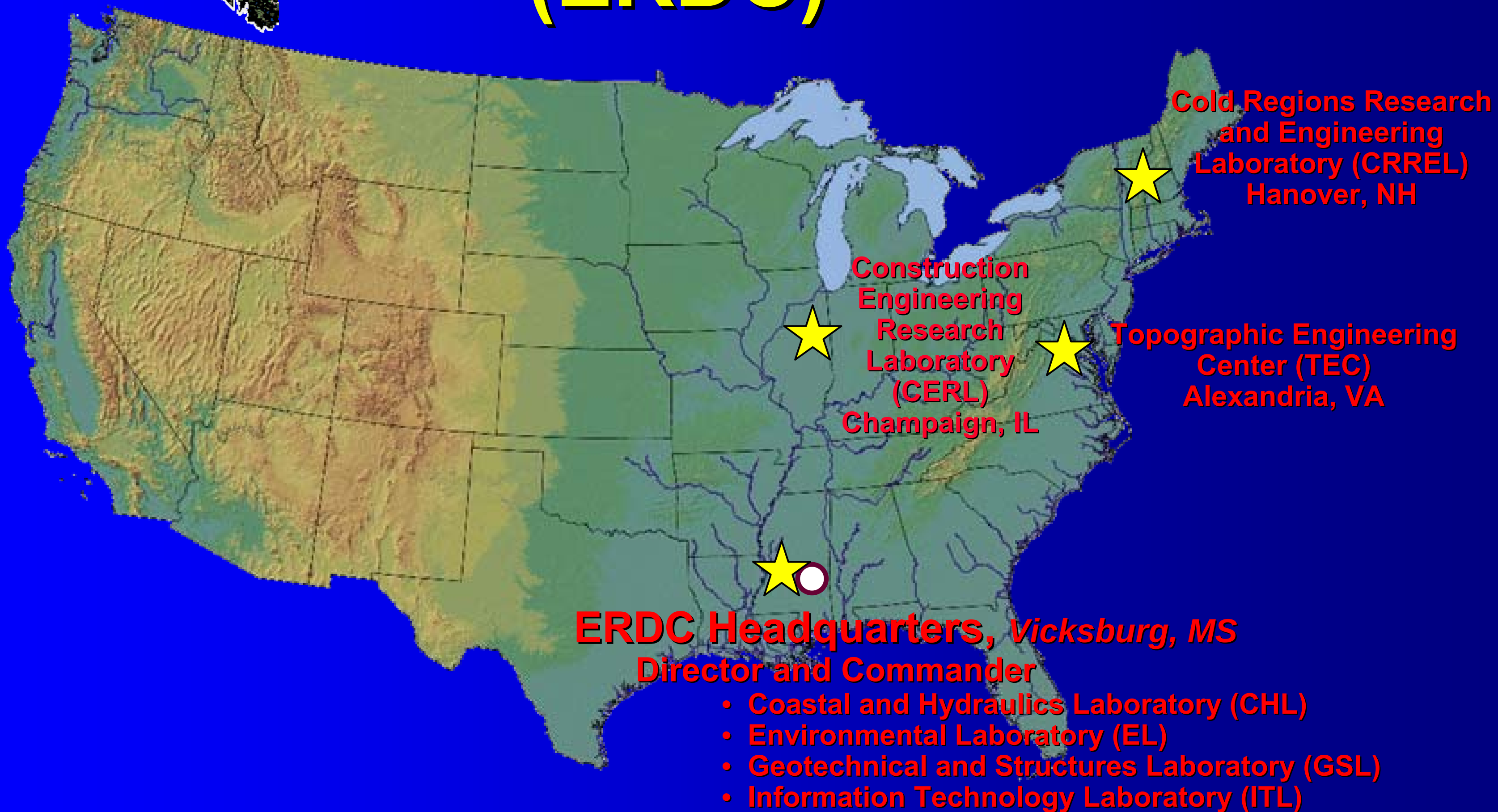
24 JAN 07

Presentation Outline

- Introduction
- Power & Energy Technology Requirements & Goals
  - Installations
  - Warfighter
- Selected Initiatives

Engineer Research and Development Center (ERDC)



ERDC-CERL Team & Collaborators

ERDC-CERL Researchers

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Roch Ducey
Elect. Engineer

Tarek Abdallah
Elect. Engineer

Dr. Chang Sohn
Mech. Engineer

Joe Bush
Mech. Engineer

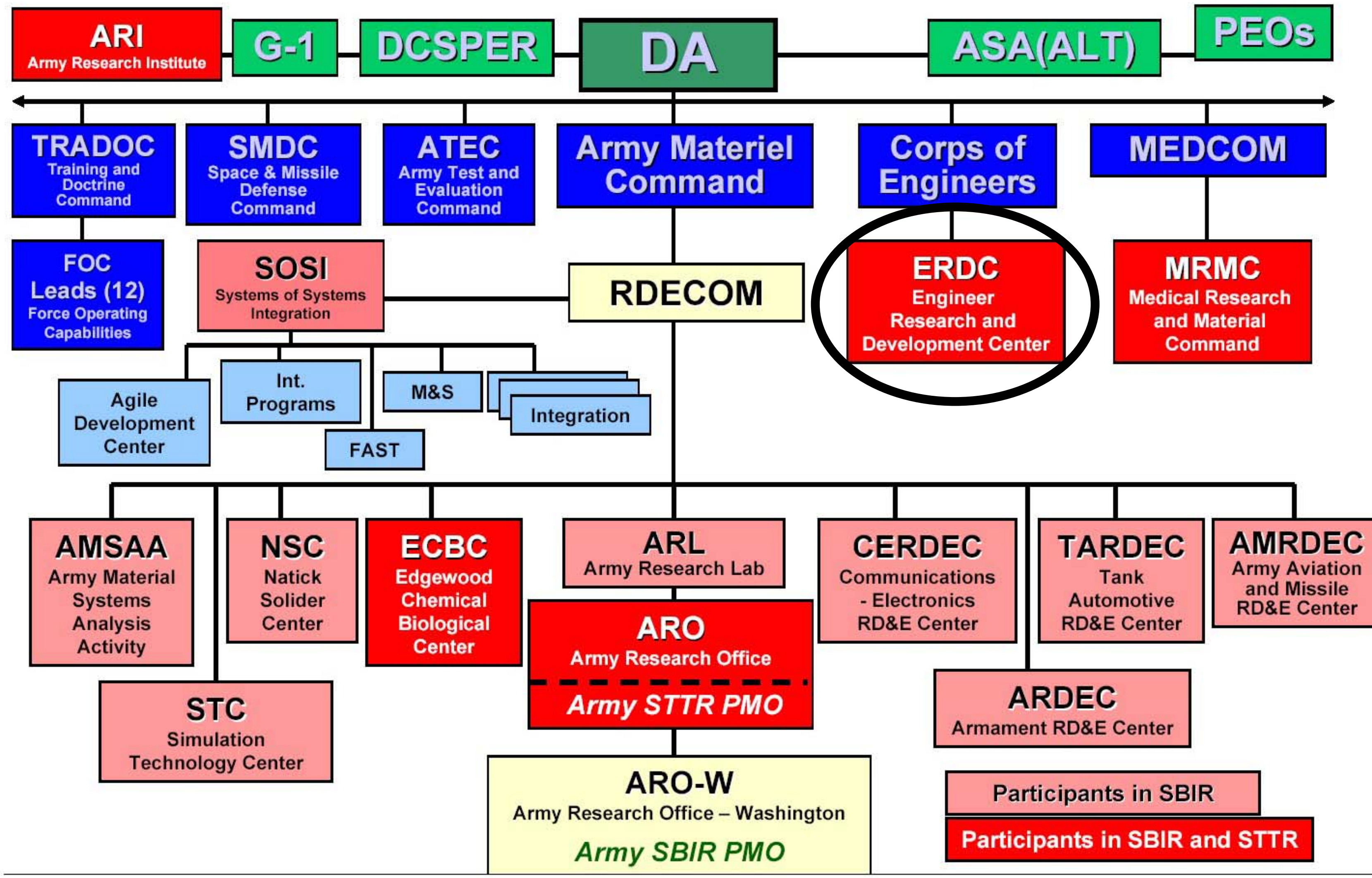
Nicholas Josefik
Mech. Engineer

Scott Lux
Elect. Engineer

Dr. Carl Feickert
Physicist

Major Collaborators

ARMY R&D Organizations



Army Energy Strategy for Installations

- The Strategy sets forth the Army's energy goals for 25 years and the Campaign Plan defines the intermediate actions, approaches, initiatives and funding over the 25 years to ensure the Army successfully achieves long-range energy and water management goals.

- The 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

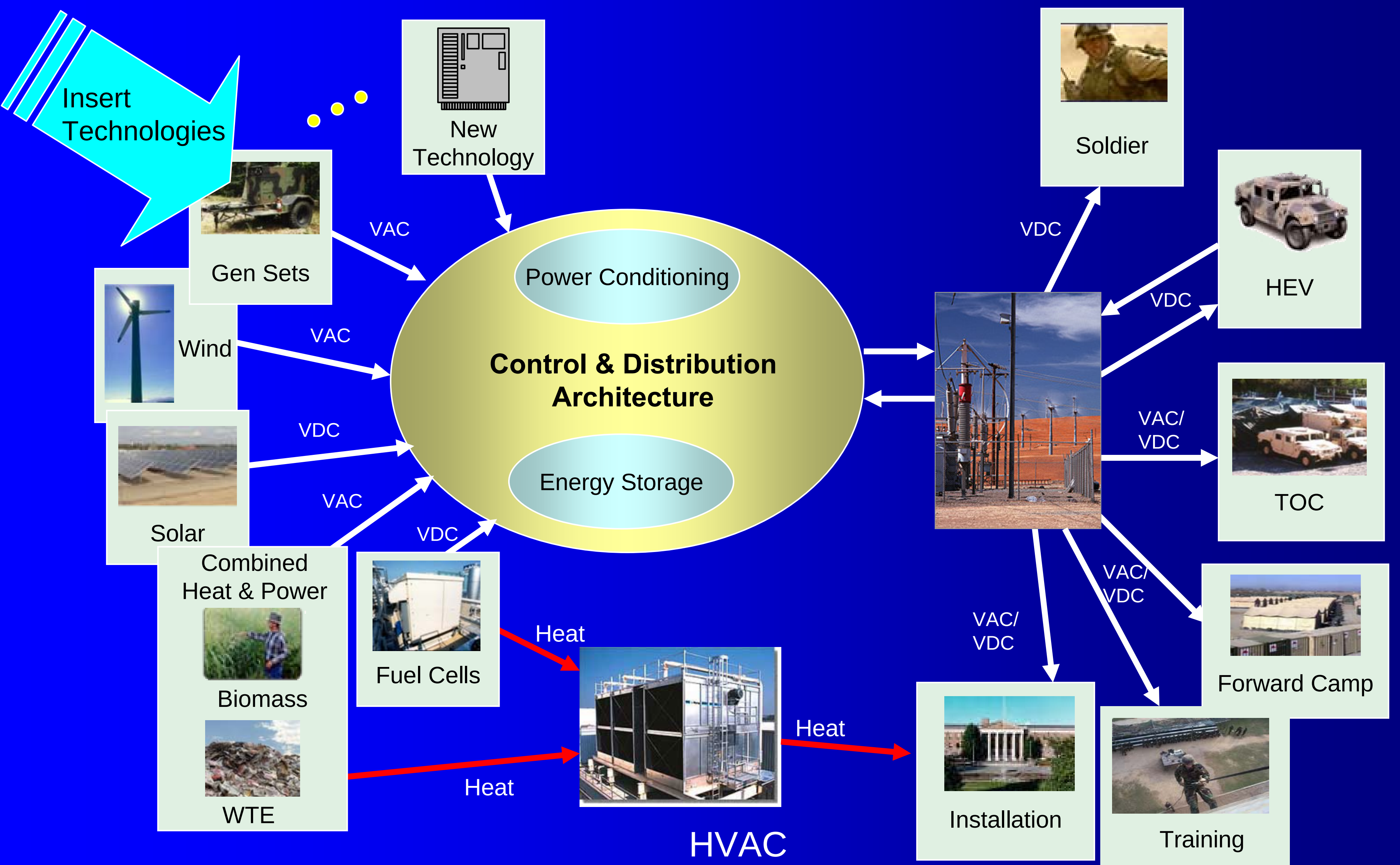
- References
  - http://hqda-energypolicy.pnl.gov/programs/plan.asp
  - The Secretary of the Army and the Army Chief of Staff signed the Army Energy Strategy for Installations on 8 July 2005. http://hqda-energypolicy.pnl.gov/docs/draft_strategy.pdf

2005 Energy Policy Act

- The Domenici-Barton Energy Policy Act of 2005 was signed by President Bush on 08 AUG 05. Army / DoD related guidance includes:
  - Directs the federal government to use more renewable energy, with a goal of using 7.5 percent or more by 2013.
  - Directs the federal government to meter or submeter all federal buildings by October 1, 2012.
  - Requires a 20 percent reduction in federal building energy use by 2015.
  - Provides funding for energy efficiency programs for public buildings, including schools and hospitals.
  - Increases fuel efficiency requirements for federal vehicles.
  - Directs the DOE to fund selected demonstration projects that involve using hydrogen and related products at existing facilities or installations, such as existing office buildings, military bases, vehicle fleet centers, transit bus authorities, or units of the National Park System.
  - Requires sustainable design principles to be applied to the siting, design, and construction of all new and replacement federal buildings.
  - Green procurement guidance.

- References
  - http://energycommerce.house.gov/108/energy_pdfs_2.htm

Vision for Army Power Delivery
Home Station-to-Foxhole



Technology Advances Needed to Achieve Future National Power Delivery System (Ref)

- Smart power delivery system
- Advanced distribution automation
- Fast simulation and modeling
- Integrating distributed energy resources
- Distributed storage technologies
- Power system operation and control
- Reduce vulnerability to natural disaster & attack
- Improve power quality

Army challenge adapt national tech advancements to blend with & scale the power vision home station-to-foxhole

Ref: *Power Delivery System and Electricity Markets of the Future*, EPRI, Palo Alto, CA: 2003. 1009102

Power & Energy Technology Warfighter Goals

- **<u>Provide Warfighter Payoff!</u>**
- **Meet Unique Operational Needs Of Each Service**
- **Compatibility With Diesel Fuel Logistics**






TRADOC Pamphlet 525-66 (refers to Force Operating Capabilities (FOCs))

- **FOC-08-04: Installations as our Flagships**
  - Capstone Capabilities.
    - The role of installation is shifting to continuous support from home station to foxhole.
    - These capabilities apply to our permanent installations at home and abroad, as well as to those that support expeditionary and contingency activities.
  - In addition or adjunct to installation natural and built infrastructure needs inculcated into the other FOCs, the following encompasses those focused capabilities most critical to achieving required installation support for the Army:
    - Provide Power Projection
    - Maintain Readiness
    - Maintain Quality of Life
- **References**
  - http://www.tradoc.army.mil/tpubs/pams/p525-66.htm

TRADOC Pamphlet 525-66

- **FOC-09-03: Power and Energy**
  - Capstone Capabilities.
    - Improve both strategic responsiveness and core warfighting abilities to effectively fight as an integral component of a joint, interdependent, full spectrum, mission-tailored force,
    - Optimize combat effectiveness via consumption reduction, alternative generation, management, and distribution of power and energy across the force, for all systems—automotive, electrical and soldier.
  - (2) The use of a single fuel for both ground and aviation will simplify support operations. Efficiencies gained through improvements in the engineering and manufacturing processes will lessen fuel requirements for ground vehicles.
    - Fuel cells and other in-place technologies will negate the need for storage of large quantities of bulk fuels for ground vehicles alone.
  - (3) The use of alternatives to fossil fuel, including fuel cells, fusion, fission, hydrogen energy, renewable sources, biomass, and magnetohydrodynamic thrusters, must be pursued for significant advances in efficiency to be made.
    - Systems of the future will look at power storage and distribution as two halves of the same whole, rather than as disparate systems.

Forward Deployments

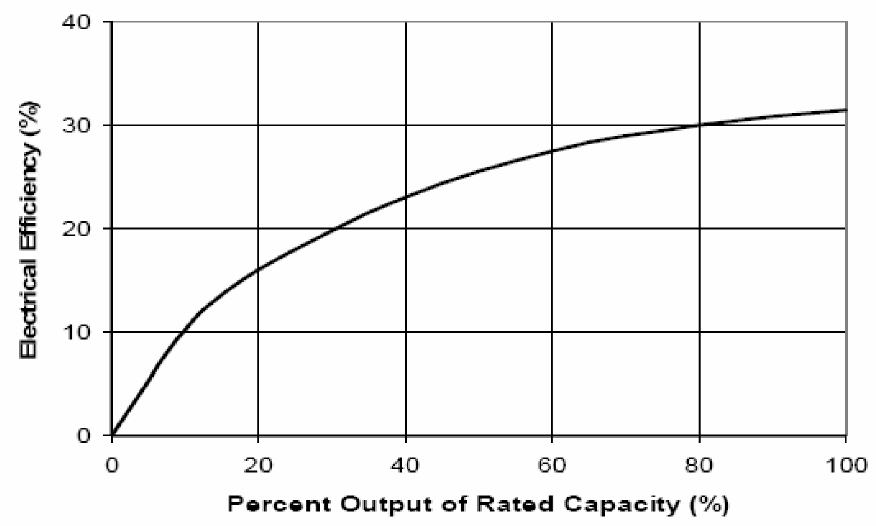
- Base Camps
- Life Support Areas
- Advanced Operations Base
- Forward Operations Base
- Tactical Operations Center

- Fuel Related Casualties
- Waste Disposal also an Issue

Military GenSets & Efficiency

Current DoD GenSet (2 kW – 60 kW) Inventory

Unit Rating (kW)	No. of Individual Units	Total Capacity (kW)
2	10,979	21,958
3	39,789	119,367
5	17,603	88,015
10	13,745	137,450
15	5,411	81,165
30	6,669	200,070
60	6,495	389,700
Total	*100,691*	*1,037,725*



Partial Loading = Very Low Efficiency

3 kW System

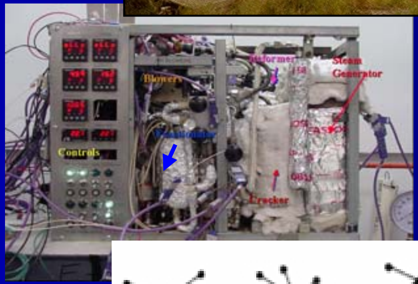
30 kW System

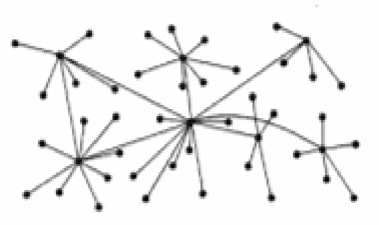
60 kW System

Related Initiatives

- **Scalable and Dynamic Power Delivery Systems for Military Installations**
- **Congressional Projects**
  - Fuel Cell Demonstrations Tailored for Army Needs
  - Next Generation Fuel Cell Technology Development
- **DOE Interagency Agreement**
  - Energy Conversion, Energy Storage, Power Conditioning Support to FutureGen Project
- **National Military Command Center (NMCC) Support**
  - Designed, Installed, Tested Control Sys for Backup Switchgear
- **New Small Business Innovative Research (SBIR) Topics**
  - Intelligent Tactical Electric Grid Control
  - Hydrogen Reformation of Renewable Ethanol for Military Applications
- **Waste to Energy ECIP Project at Fort Stewart GA**
  - Co Production of Hydrogen, Heat, and Electricity via Fuel Cell

Current Leveraging Initiatives





- **University of CA – Irvine / TARDEC → MOU**
  - “Silent Watch” Modeling and Simulation
- **249th Engineer Battalion / Mobile Electric Power**
  - “Silent Camp” Scoping
- **Fuels Reformation**
  - Logistic Fuels, Ethanol, Other Bio Fuels
- **Various CRADAs with Industry Partners**
- **Installation Electric Power Microgrid**
  - RDECOM P&E IPT, Sandia National Lab Energy Surety, SERDP Proposal
- **Army Energy Security Workshop**
  - NCA&T University Collaboration, DEC 2006

Backup Slides

- Selected Publications & References
- FY07 Waste to Energy ECIP Project-Fort Stewart
- DoD PEM & PAFC Demonstrations
- “Silent Camp” Concept
- Stryker Vehicle Silent Watch Concept
- DoD Fuel Cell & H2 Initiatives Website

Selected Publications & References

- Military Requirements of JP8 Reformers
  - http://www.cecer.army.mil/techreports/Holcomb_JP8_Requirements___TR/Holcomb_JP8_Requirements___TR.pdf

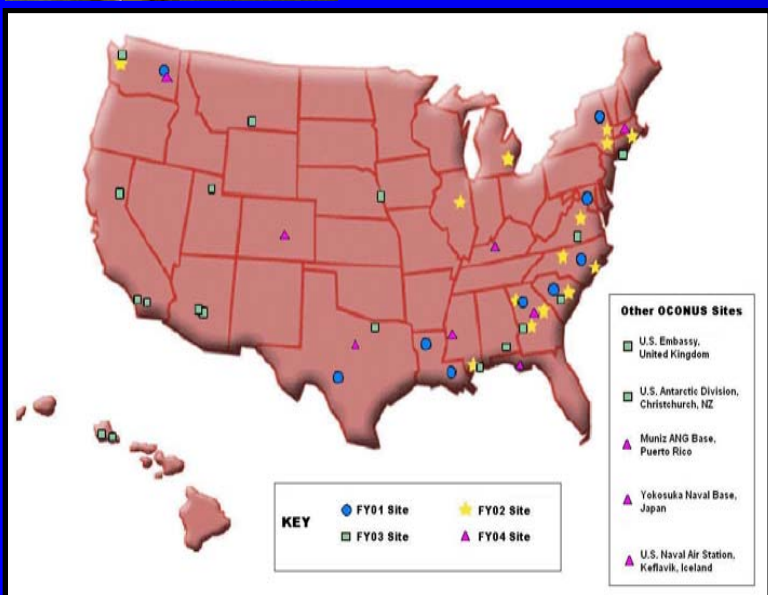
- Control Dynamics of Adaptive and Scalable Power and Energy Systems for Military Micro GridsReport
  - http://www.cecer.army.mil/techreports/ERDC-CERL_TR-06-35/ERDC-CERL_TR-06-35.pdf

- PEM Fuel Cell Demonstration Volume II Report
  - http://www.cecer.army.mil/techreports/White_PEM_Vol2___TR/White_PEM_Vol2___TR.pdf

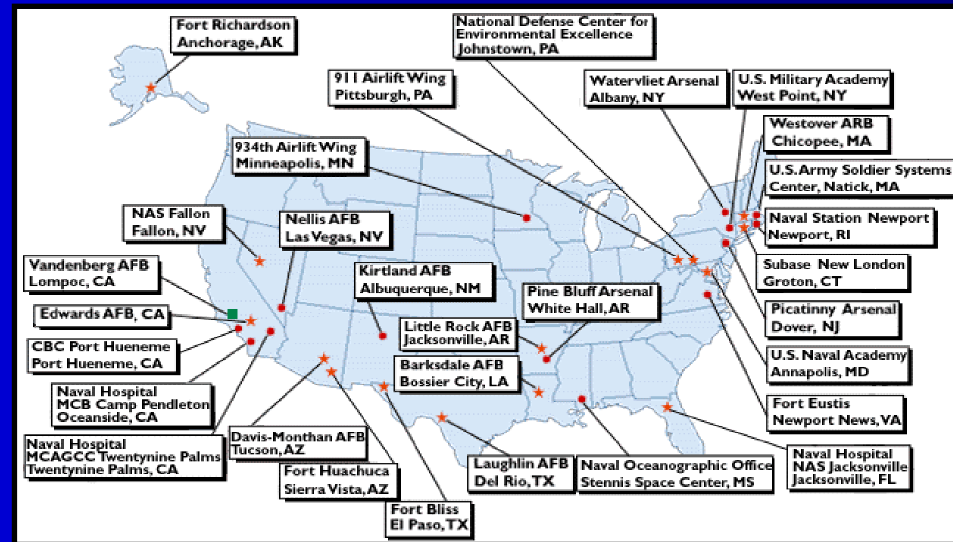
- Fort Stewart Waste to Energy (H2) Report
  - http://www.cecer.army.mil/techreports/Holcomb_CERL_TR-06-07/Holcomb_CERL_TR-06-07.pdf

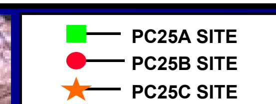
FY93-FY94 Phosphoric Acid Fuel Cell (PAFC) Project Sites

90 Fuel Cells
56 Sites
5 Manufacturers



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





30 Fuel Cells
30 Sites
1 Manufacturer

Stryker Vehicle With MREF-APU

"Silent Watch" Capability

HyPM 7

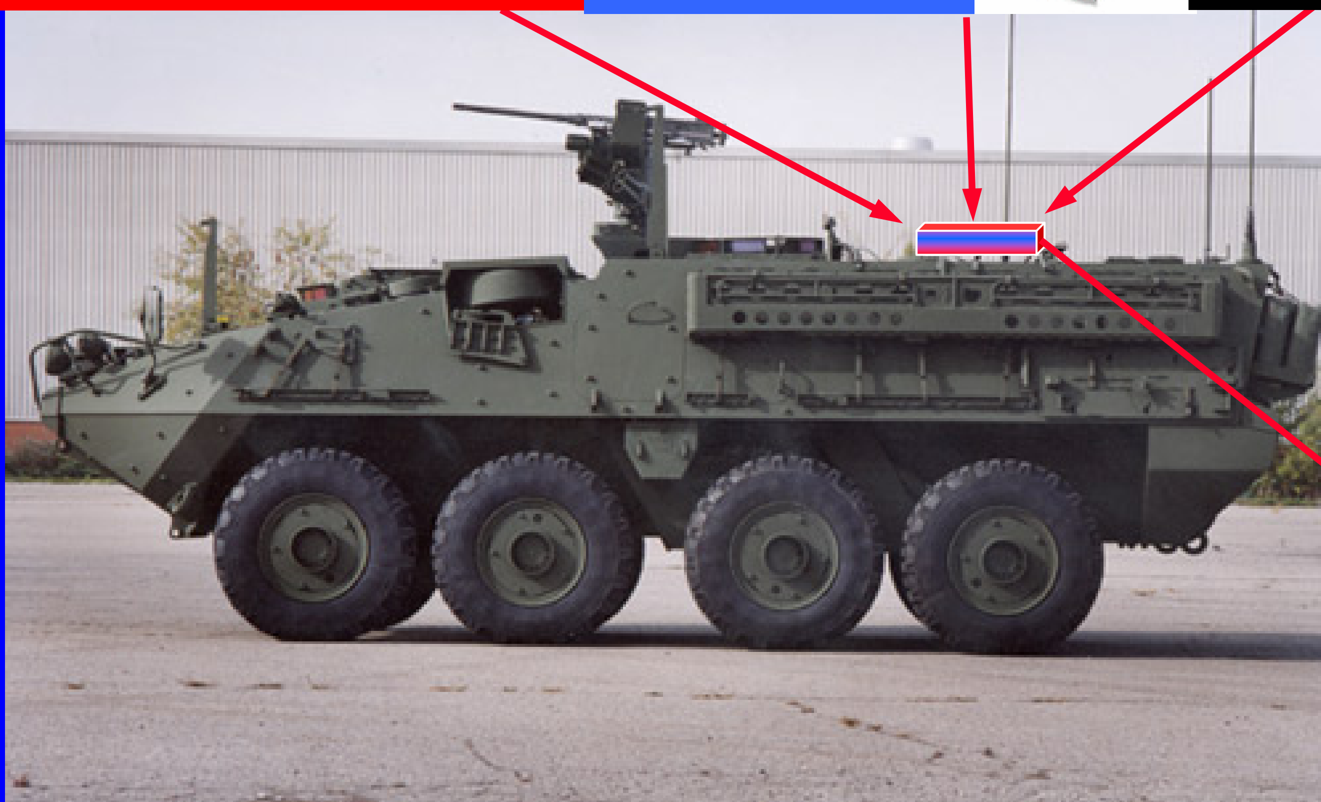
Generates power on-demand for silent watch mission use.

HyLZER 2.0

Generates Hydrogen for storage and later use by HyPM 7

Metal Hydride

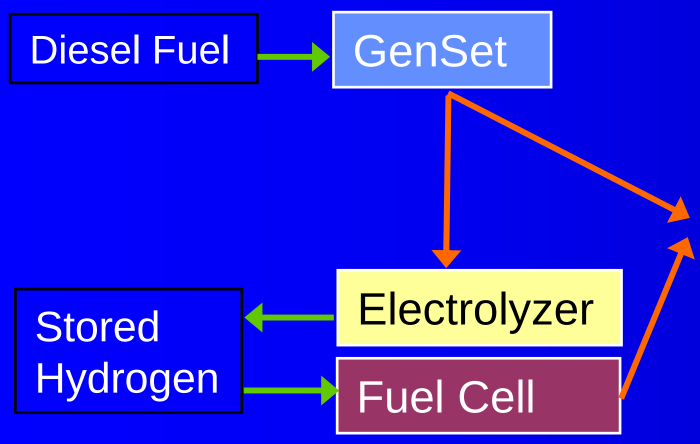
Stores Hydrogen at low pressure for use on-demand by HyPM7 during power generation

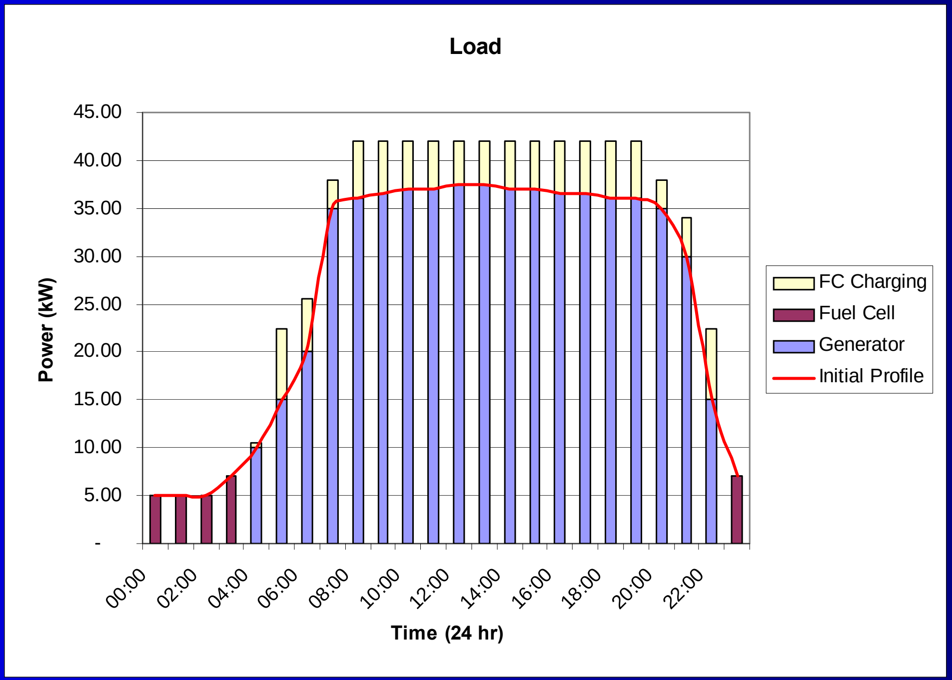


Current Prototype System is located behind turret and in front of the rear hatch ports of egress. System also includes on-board water storage vessel.

Silent Camp Concept

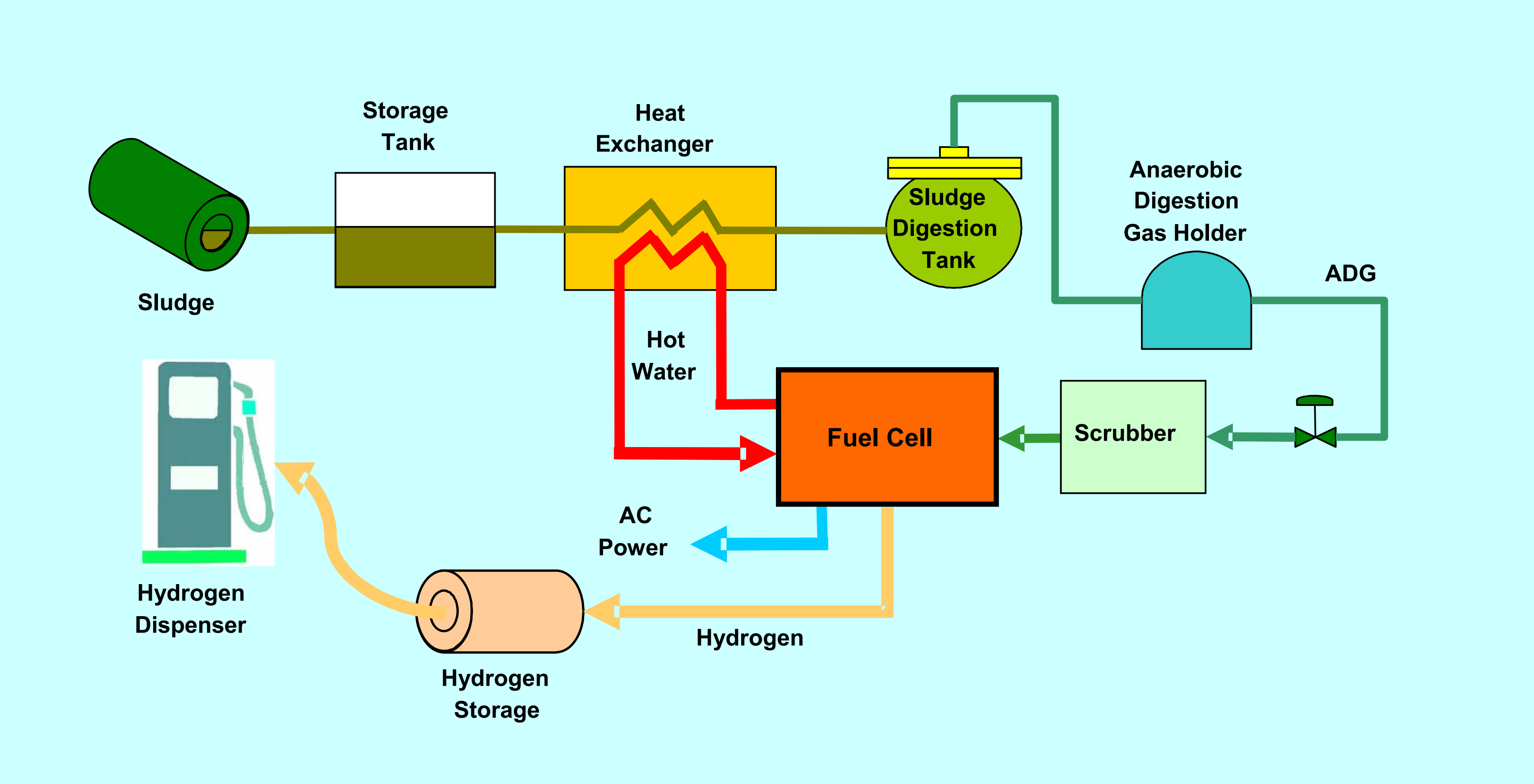
- Increase GenSet Output to Electrolyze Water
- Store H2 Produced from Electrolyzer
- Use Stored H2 and Fuel Cell to Power Loads at Night
- Shut GenSet Off During Fuel Cell Operation
- Can Maximize Silent Camp Operation or Fuel Savings





24 Hour Load Profile

FY07 Waste to Energy Energy Conservation Investment Program (ECIP) Project



www.dodfuelcell.com

Session 1

Jones

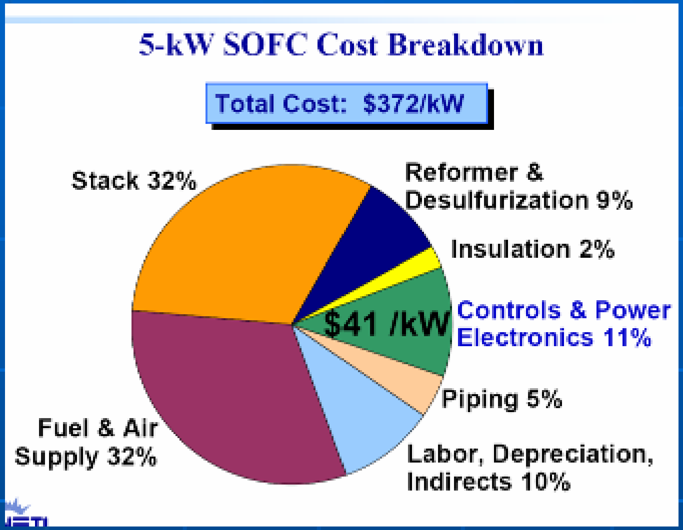
Advanced Technology Goals for High Megawatt Applications

Edward Jones
DOE Office of Clean Power Systems
January 24, 2006

The PCS Problem

- *"It is our assessment that state-of-the-art power conversion technology is not capable of converting the low voltage, high current dc quantity into a high voltage, low current ac quantity within the target cost of $40/kW and acceptable availability numbers."*

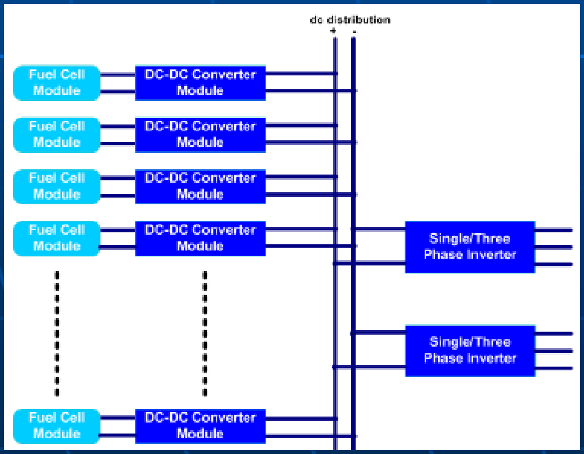
  --Ralph Teichmann, GE



Artist's depiction of FutureGen

Production Scale

- "Why not just use many kW-scale inverters?"
- Translation: modular topology?



DC Bus SECA interconnection
Burak Ozpineci, ORNL

Cascade multilevel inverter
Fang Peng, MSU

Voltage Step-up and Isolation

- Step up stack voltage (<1kV) to 18kV for grid, and provide galvanic isolation

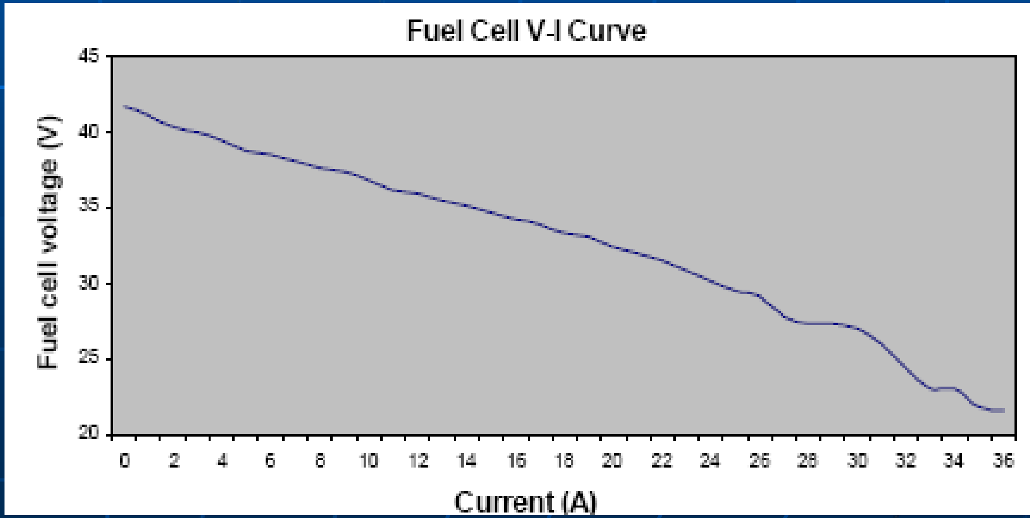
ABB autotransformer

Jason Lai's (VA Tech) DC-DC converter for kW SECA

- Conventional vs. Solid-state transformer

Storage

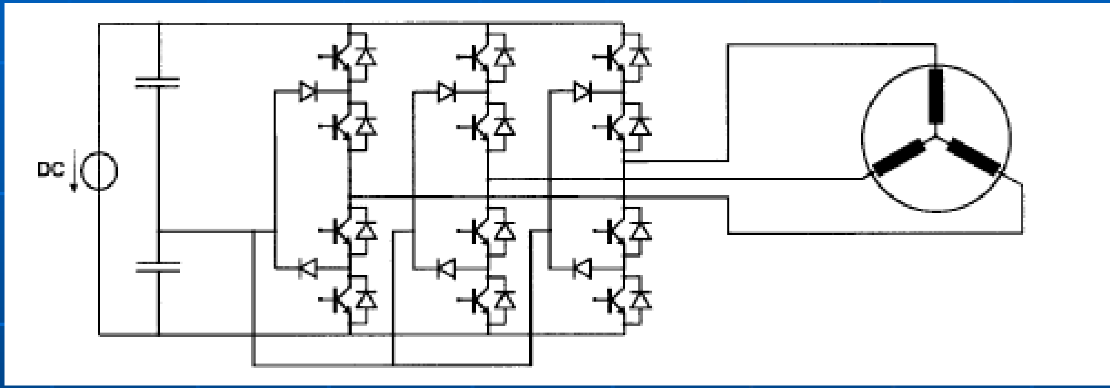
- Fuel cells have slow response to changing load
  - Tenths of seconds vs. milliseconds
  - The fuel flow rates cannot be adjusted rapidly and the internal chemistry must reach equilibrium before the cell can support increased load
- Auxiliary power is needed for start-up and to power control signals



Prasad Enjeti, Texas A&M

Ripple & Power Quality

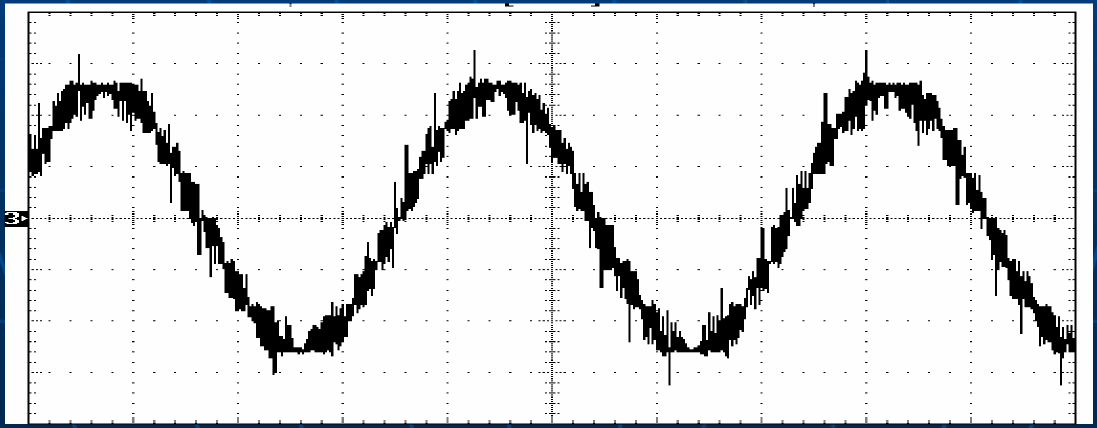
- Three-phase harmonic cancellation



Nikolaus Schibli

EPFL

- Ripple reduction in DC-DC converter



Prasad Enjeti

Texas A&M

Efficiency Improvements

- Advanced materials (i.e. SiC) and switch technology (i.e. IGCT)

1200V IGBT w/SiC Schottky
Jim Richmond, Cree

ABB IGCT
Prasad Enjeti, Texas A&M

- Soft switching and high frequency

Reliability, Durability, & Thermal Management

- Minimum reliability and durability requirements

Fairchild semiconductor

From Wikipedia

- Component temperature limits

Footprint

- An issue?
- High frequency to reduce passive components

Answering The Questions

- Discuss these issues as they arise today
- E-mail me: Edward.Jones@hq.doe.gov
- E-mail anyone, keep the discussion going

Session 2a

Berntsen

FuelCell Energy

Needs and Wants- Suggestions for High Voltage and High Megawatt Applications

George Berntsen
Manager, Electrical & Controls Engineering
FuelCell Energy, Inc.

Stack Voltage

Power plant voltage limits determined by stack electrical isolation design. Lower fuel cell stack voltage differential desired to:

- Minimize stack electrical isolation requirements
- Reduce fuel cell cost
- Simplify design

Higher fuel cell voltage (to 750V, 1000V?) desired to optimize Power Conversion:

- Reduce Inverter cost & size
- Enhanced Inverter efficiency

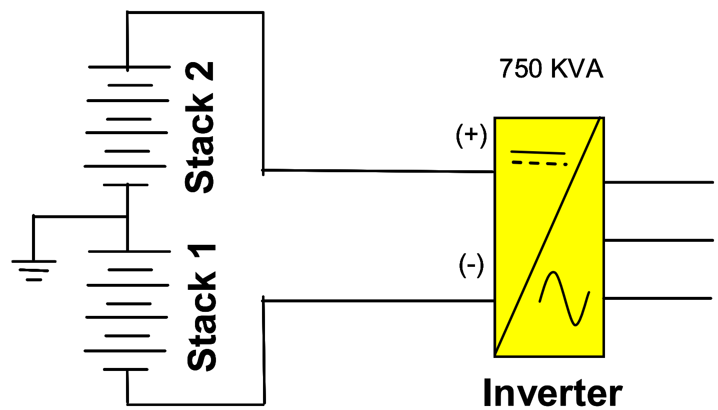
Stack Voltage

Need to evaluate trade-offs:

- Engineer stack and inverter configuration for optimal voltage output:
  - Cost
  - Performance (efficiency)
  - Reliability

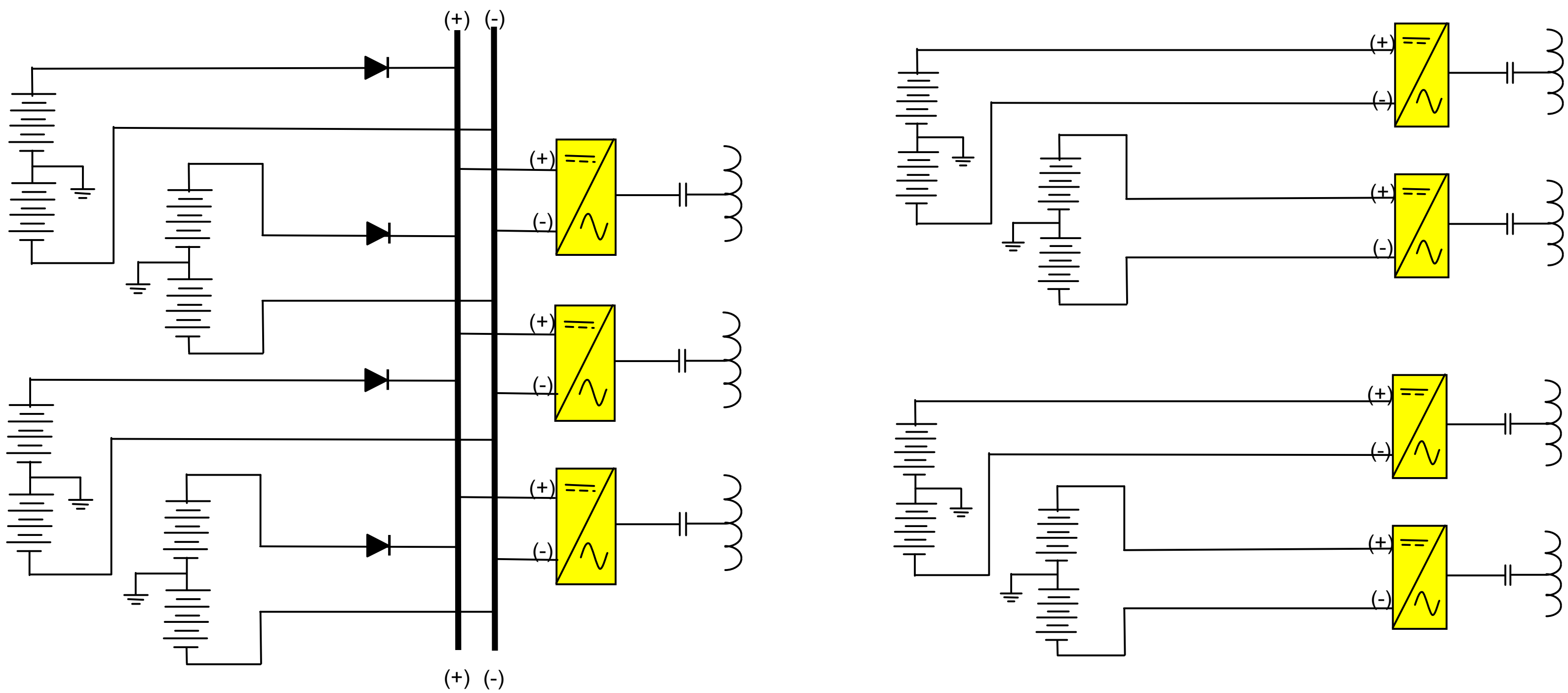
One Option Being Considered: Series Connect Stack Pairs

- Minimizes Stack-to-Ground Voltage
- Maximizes Inverter Voltage Input



Inverter Input

Common DC Bus or Dedicated/Segregated?



FuelCell Energy

Inverter Input

DC Bus Approach

Pros

- Optimal KVA matching of inverters and stacks ($$$ savings)
- Capable of Part load operation with failed inverter

Cons

- No ability to bias individual stack currents.

  Less than optimal fuel flow – power output matching
- Custom DC bus-work $$$
- Power Diode Losses

FuelCell Energy

High MW Application DC Bus Considerations

- How many inverters can be eliminated?
- In High Volume, would DC Bus Work costs be much less than Inverter savings?
- In High MW, Efficiency less of a constraint than capital cost reduction

Session 2a

Casey

High-Megawatt Converter Technology Workshop
January 24, 2007

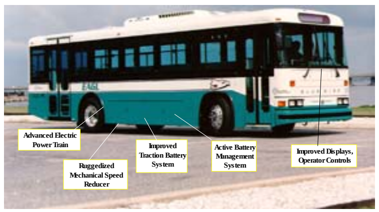
Denny Mahoney and Leo Casey
leo.casey@satcon.com

SatCon?
SatCon Highlights
Technology … Applications … Products

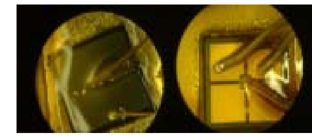
Technology

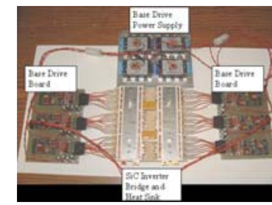
Today

- 200 Employees
- 3 Divisions



2003 Subsidiary Corporations





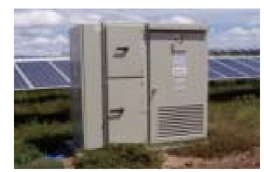
BEACON 1997

WEC/NG 1999

InverPower 2001

Patriot - 1992

FMI & HiComp 1998



Magmotor 1997

1985 MIT-DRAPER

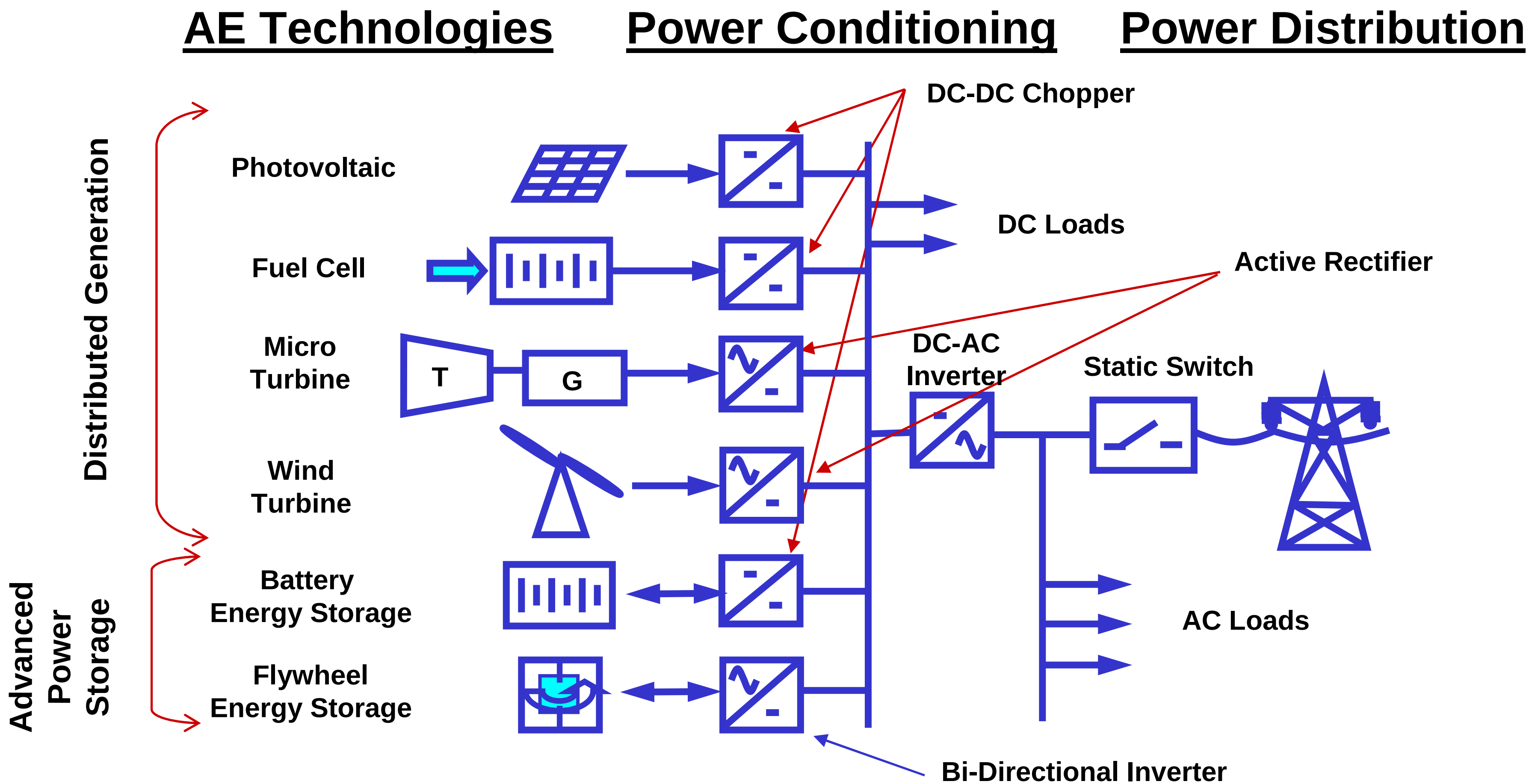
Applications

Energy Storage | *Renewable Energy* | *Distributed Energy* | *Grid Support*

Technology Development

- MIL-38534 Class K
- Outdoor Electronics with 5+ year Warranty
- R&D, e.g. SiC Applications WORK

SatCon's Focus is Grid Electronics – getting electrons on and off the Grid, reliably, efficiently, enhancing Power Q, improving System Dynamics



. . . Systems Integration Key to Meeting Requirements of AE Power Plant

Solar Inverter Product Line

POWERGATE™

30kW ←------------------------------→ ***500kW***

- Highest efficiency listed for approved CEC inverters in its power rating
- First 100 kW inverter shipped for European market
- Only 500kW solar inverter rated by the California Energy Commission

❖Additional Inverter Applications

Fuel Cells, Wind, …

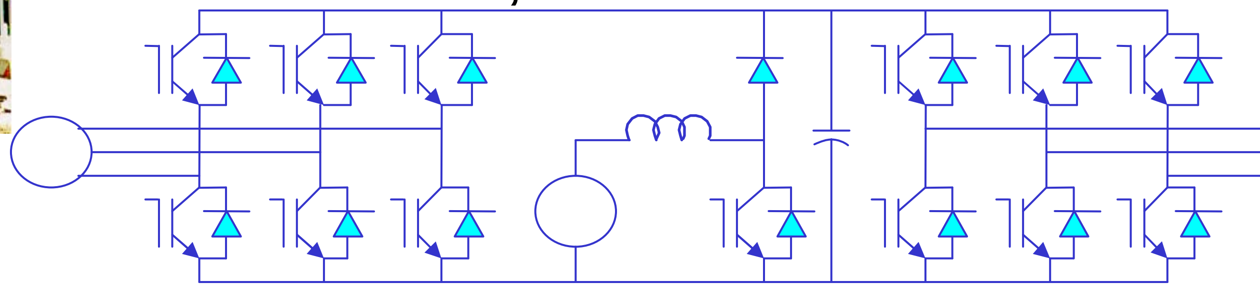
300kW ←------------------------------→ ***3MW***

As Resource (Wind, PV, FC …) Penetration grows it becomes Integral to Grid Stability and Control, SO …

SVR/DVR

- Customer interface electronics, inherently destabilizing?
- Renewable resource potentially at odds with grid
- **Or**, could enhance, P, Q, dP/dt, nf, ABC

STS



BES

RUPS/CPS

RTD

DG

UPS

IEEE1547
UL1741
CEC Rule 21
519
…
IEC

Inverter is the Glue

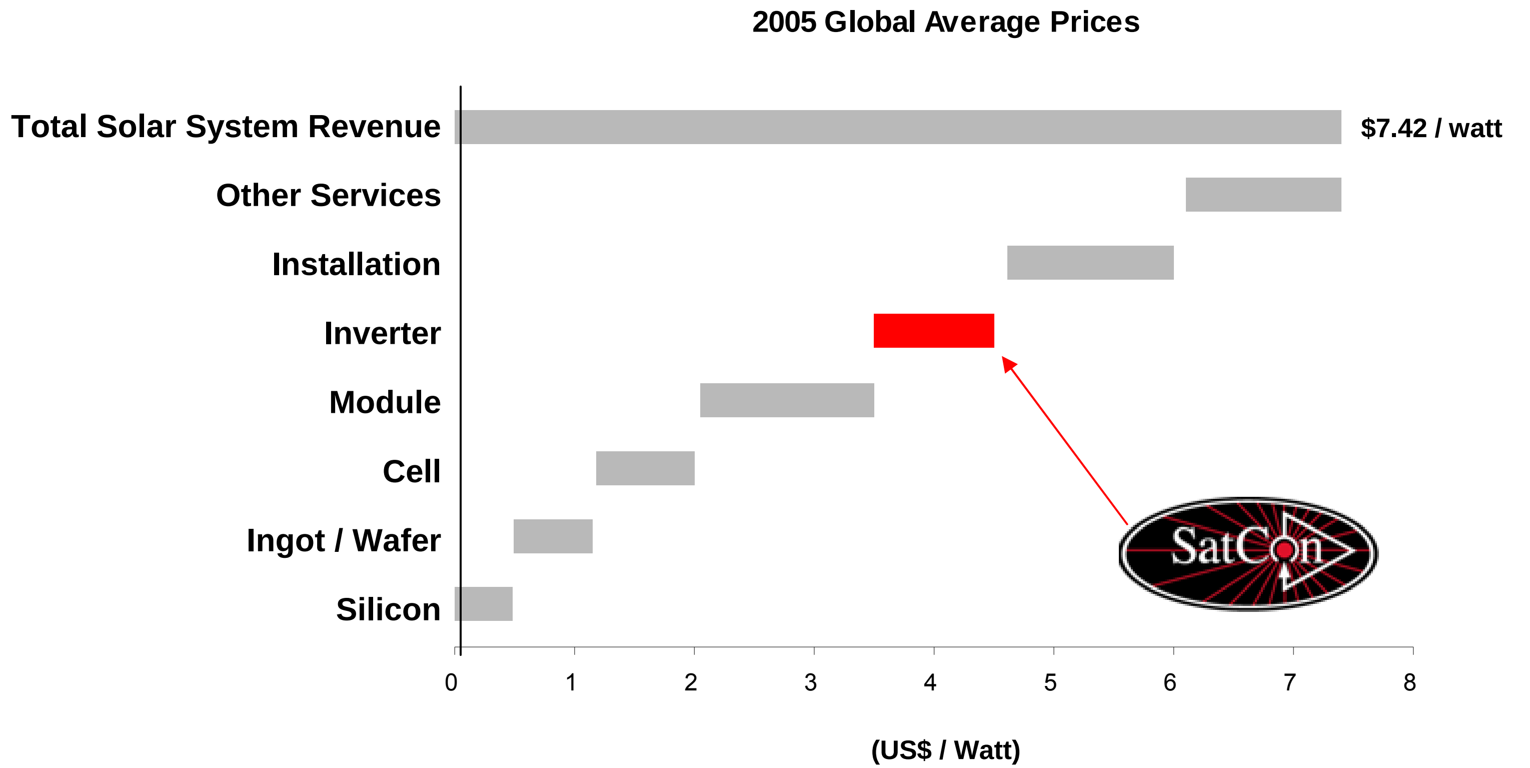
- Cost
- Performance
  - Power quality
  - Overload
  - …
- Reliability

- A Grid Inverter is not just a motor drive

- Could be much more than a thermal power plant

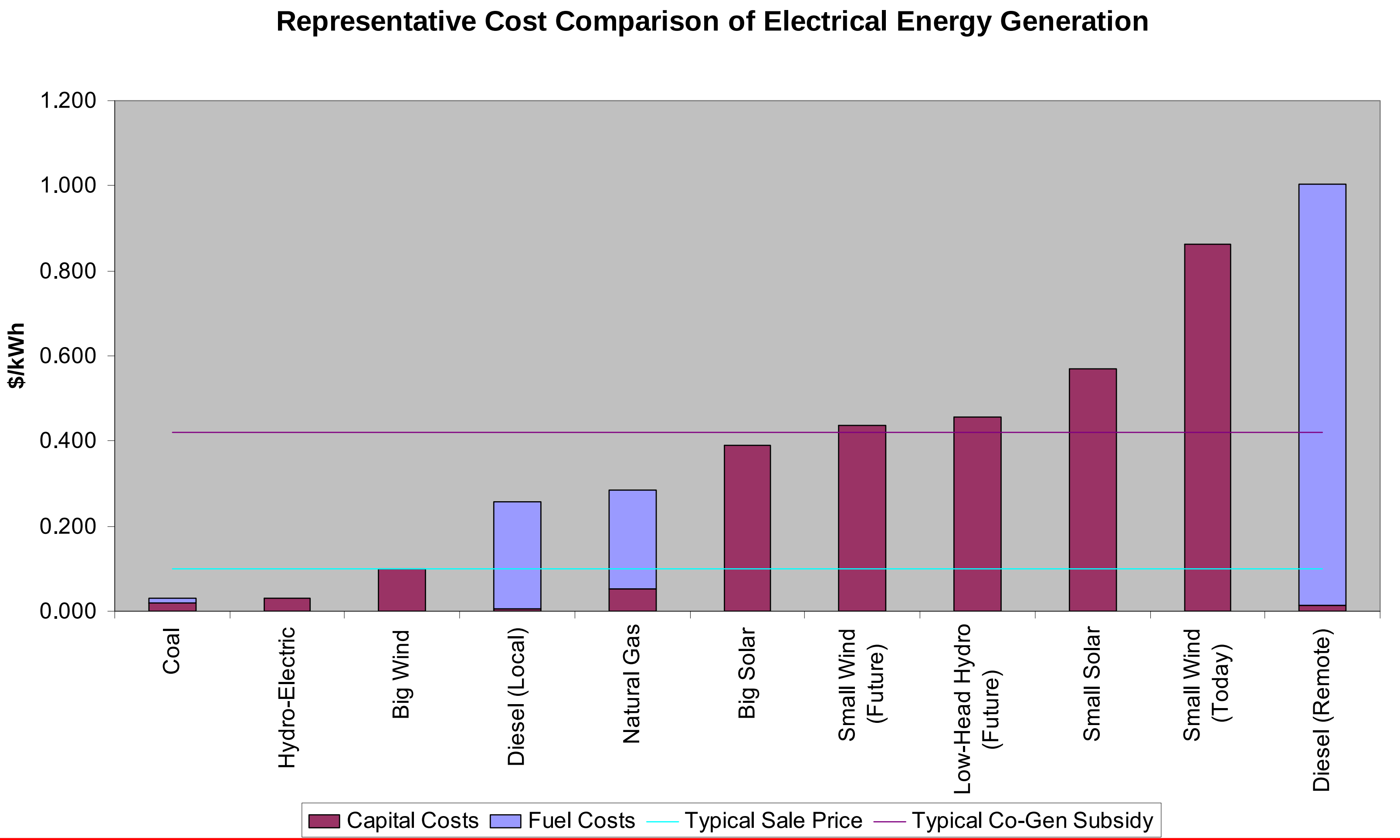
Inverters' Role in the Solar Value Chain

- Inverters make the solar power useful
- Represents approximately 7% to 10% of system cost



Source: CLSA report July 2005.

Economic Analysis



(Some) Grid Technology Developments

- Materials
  - Composites, e.g. cable
    - Replaces steel core conductor
    - 2x rating
    - eliminates sag caused by load, ambient
    - fewer structures along right-of-way
    - Reduces line losses
    - Eliminates bi-metallic corrosion, fatigue iss
  - Super conductors?
- Devices
  - Silicon Carbide (devices + related)
    - solid state breakers
    - HV, HT Electronics
- Distributed sensing
  - temp, volt, I,
- Communications
- Nuclear
- Demand side control
- Micro-grid
- Storage
- Efficiency (technology)?
- Improvments (FC, PV, Wind, ...)
- EV/HEV
- Biofuels, synthetic, cellulostic, ...
- Off-Shore Wind
- Storage, Storage, Storage, ...
-

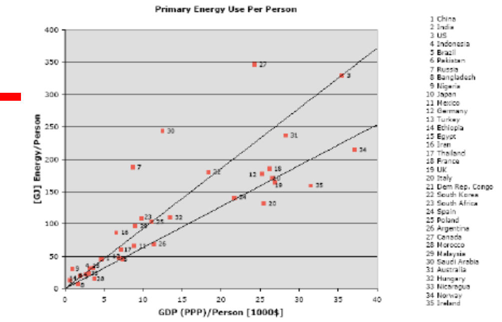
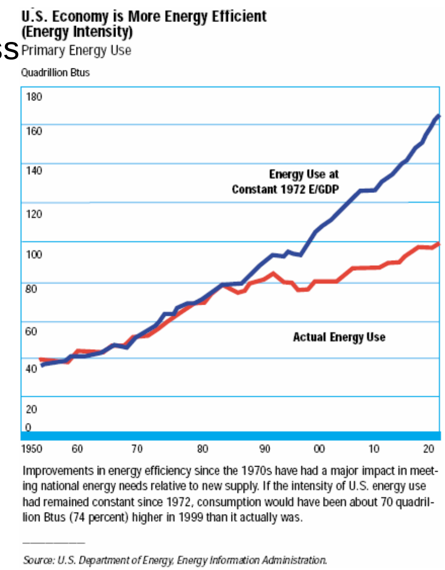


Figure 1.1 Energy use (in gigajoules) vs. GDP (on a purchasing power parity basis) for selected countries on a per capita basis. Data from the International Energy Agency. Upper line indicates ratio for the US; lower line indicates ratio for Japan and several Western European countries.



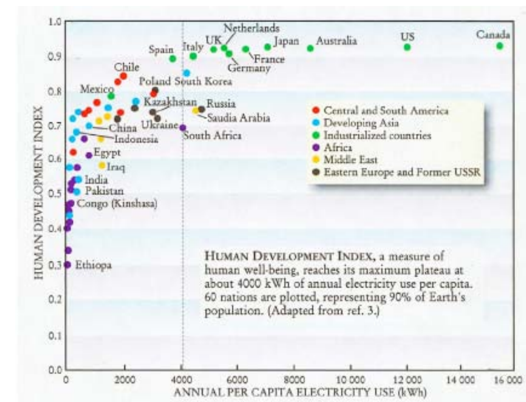
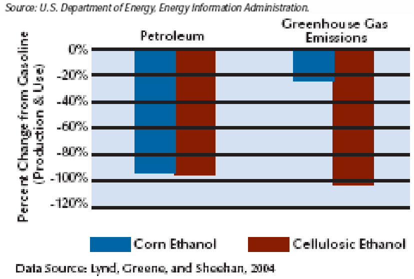
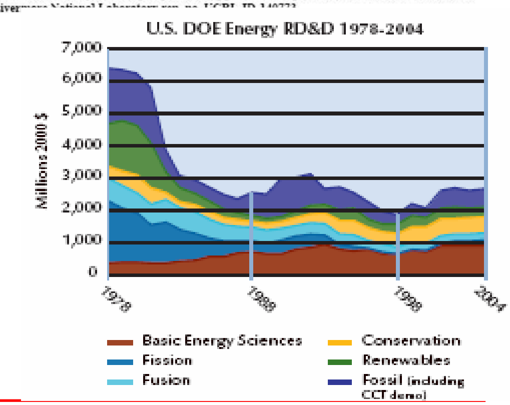


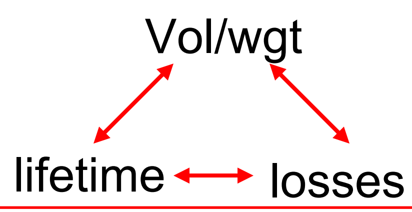
Figure 1.2. Human development index vs. per capita electricity use for selected countries. Taken from S. Benka, *Physics Today* (April 2002), pg 39, and adapted from A. Pasternak, Lawrence Liver...





Si → Si/SiC → SiC

	Silicon SOA	Hybrid Si/SiC Design	Full SiC Design
Size/Density/Efficiency	10 -- 100 W/in^3 (16 W/in^3 for SSIM)	15 -- 150 W/in^3 (25 W/in^3 for SSIM) (70% Vol., 50%Switching, ~75%P)	35 -- 350 W/in^3 (80 W/in^3 for SSIM) (30% Vol., 20%P)
Cooling	80ºC max. liquid or 25 ºC Air	80ºC max. liquid or 25 ºC Air	>100ºC liquid or 40-50 ºC Air
Response Time	10 ms for 5.6 kHz with V and I loops	5 ms for 10 kHz with V and I loops1mS for 100kHz with dead-beat control	50 µS for 100kHz with dead-beat control
High Temperature Design	Si limits entire system to < 125ºC	Si limits entire system to < 125ºC	Partial High-Temperature design then eventually complete High-Temperature design if needed (analog degradation)
Overload Capability	100-500 ms	2+ seconds	10+ seconds
Robustness/Reliability	10-20,000 hr. MTBF	20-50,000 hr. MTBF	50-100,000 hr. MTBF



Optimize Key Metric
$
Range
LCC
Life
…

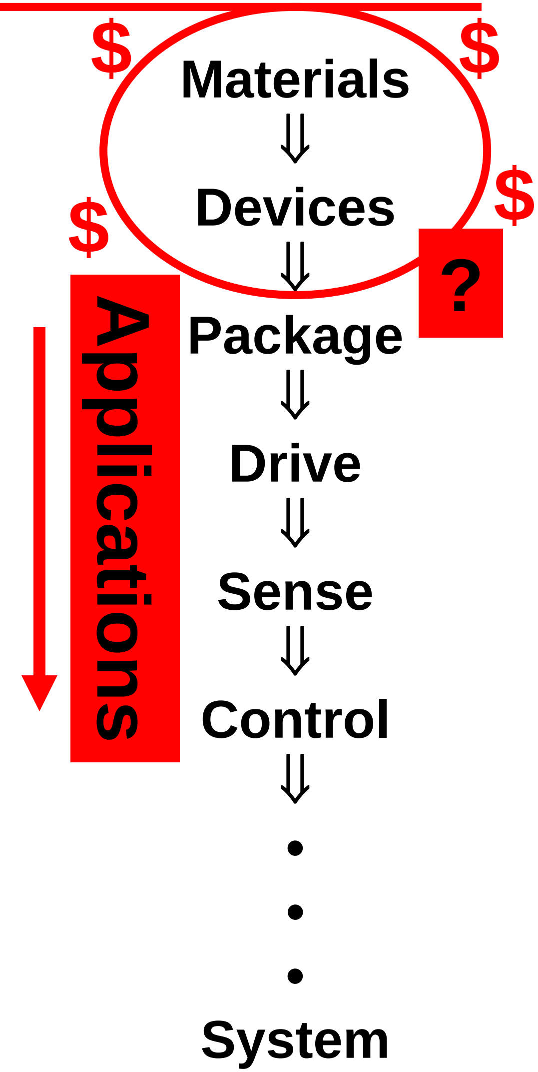
Realizing Potential of Wide Band Gap

SiC

- Power Circuits
- Power Components, active and passive
- Signal Electronics
- Control
- Software
- Thermal Management
- Mechanical Design & Packaging

Full benefit comes from addressing all areas

SiC devices are NOT drop in replacements



?

Is the performance acceptable?
Are the devices reliable?
Are they consistent (matched)?
What are the next hurdles?

Some Cost Considerations

Assume: SiC will reach 3x Si, diode is ½ of active, LC product goes down by 4, choose L or C

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

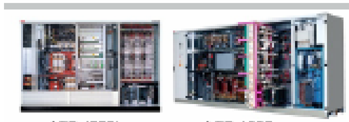
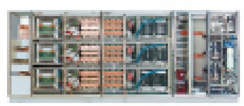
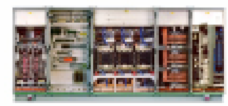
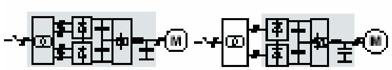
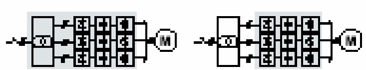
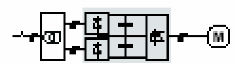
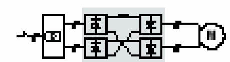
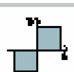
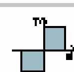
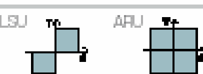
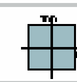
Percentage Costs for Si/SiC Inverter

1% increase, 2% improvement round-trip efficiency
For the 100kW Inverter, feeding a 200kWHr battery, once per day charging cycle 2kWHr saving of off-peak energy, 2KWHr of peak electrical energy.
German feed in tariff for PV as an indicator (~55 c€/kWh) we could argue that the 1% of efficiency is worth US $1/day, or with a 20% return on investment approximately $1,800
on the order of 10% of the parts cost of the inverter and so the increase in cost of the semiconductors in moving to a hybrid Si/SiC IGBT module is easily justified in savings due to improved efficiency
Or CEC have put a monetary value on KW capability of up to $3.50/watt and so the 1% efficiency improvement would have a direct monetary value in a subsidy situation of up to $3,500. Could be more for roundtrip and with 2 stage

Other factors: EMI, Snubbers, metal, MOVs, Electrolytics!, …

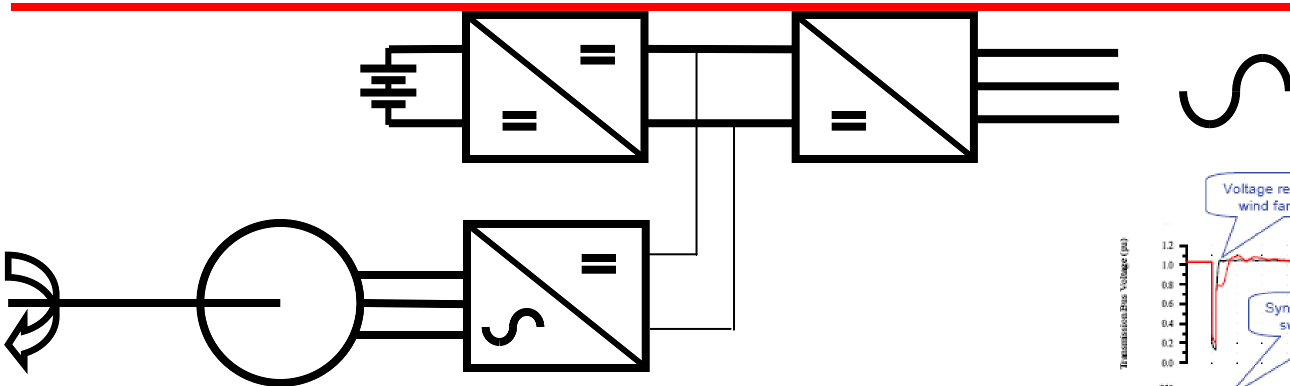
Medium Voltage Drives Today

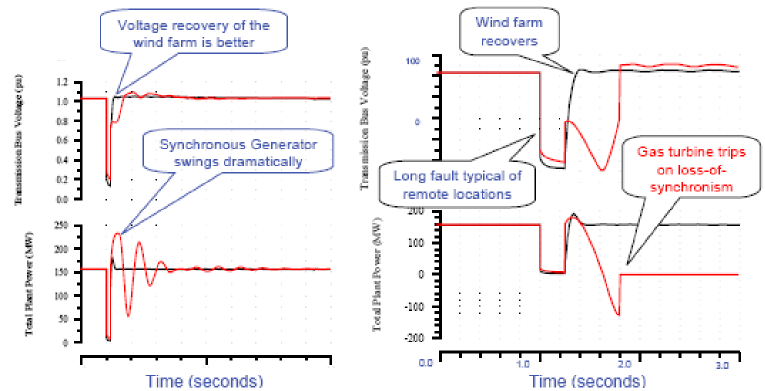
ABB, NishiShiba, Siemens, …

VSI-NPC Voltage Source Inverter Neutral-Point Clamped	VSI-MF Voltage Source Inverter Multilevel-Fuseless	VSI-NPC Voltage Source Inverter Neutral-Point Clamped	LCI Load Commutated Inverter
Pumps, fans, conveyors, extruders, mixers, compressors, grinding mills, suitable for retrofit of existing motors	Compressors, extruders, pumps, fans, grinding mills, conveyors, marine propulsion, bar and rod mills, blast furnance blowers, gas turbine starters	Pumps, fans, conveyors, extruders, compressors, grinding mills, marine propulsion, rolling mills, mine hoists	Compressors, pumps, fans, blast furnace blowers, pump storage plants
 ACS 1000i ACS 1000	 ACS 5000	 ACS 6000	 MEGADRIVE-LCI
			
Air (A) / Water (W)	Air (A) / Water (W)	Water (W)	Air (A) / Water (W)
A: 315 kW – 2 MW W: 1.8–5 MW	A: 2–7 MW W: 5–24 MW	W: 3–27 MW	A: 2–31MW W: 7–72MW / higher on request
Diodes: 12/24-pulse rectifier	Diodes: 36-pulse rectifier	Diodes: 12/24-pulse rectifier (LSU) or IGCT: Active rectifier (ARU)	Thyristors: 6/12/24-pulse rectifier
IGCTs: 3-level VSI, sinusoidal output	IGCTs: 5-level VSI-MF, 9-level output waveform	IGCTs: 3-level VSI, 5-level output waveform	Thyristors: 6/12-pulse inverter
2.3/3.3/4.0/4.16 kV Optional: 6.0/6.6 kV with step-up transformer	6.0–6.9 kV Optional: 4.16 kV	3.0–3.3 kV Optional: 2.3 kV	2.1–10 kV
66 Hz (optional 82.5 Hz)	75 Hz (higher optional)	75 Hz (Twin: 250 Hz)	60Hz (optional 120Hz)
> 45 Hz (max. 1:1.5)	> 30 Hz (lower optional)	> 6.25 Hz (max. 1:5)	Customized
			
* Sinusoidal output * Constant network power factor over whole speed range * DTC (Direct Torque Control) * Fuseless	* Constant network power factor over whole speed range * DTC (Direct Torque Control) * Fuseless	* Constant network power factor over whole speed range * Optimized pulse pattern to minimize network harmonics (with IGCT) * DTC (Direct Torque Control) * Multi-motor drives with common DC bus * Fuseless	* Soft start of large synchronous motors and generators * Fuseless

Voltage, frequency, performance tradeoff

Fully Rated Inverter provides Many Possibilities

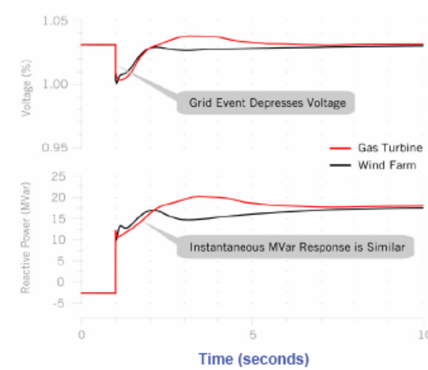




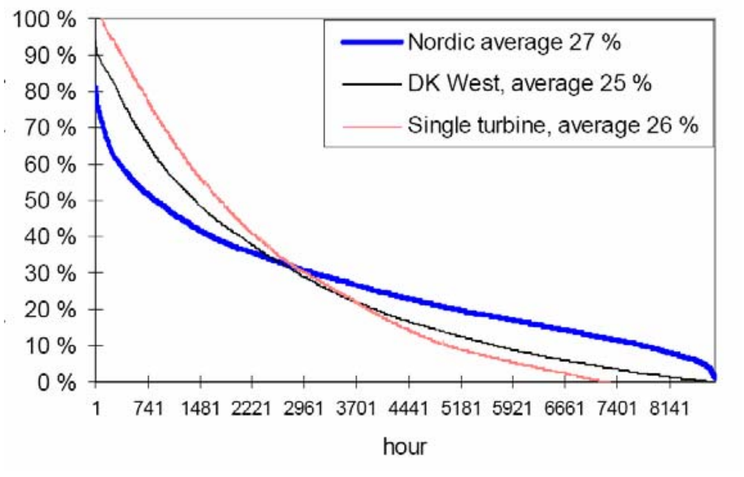
- Controllable (remotely)
- Supply Real Power, P, regulate battery

- 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!!
-

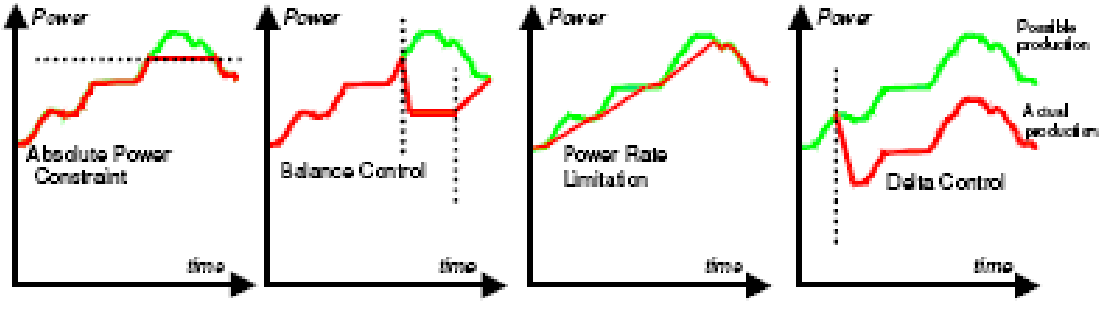


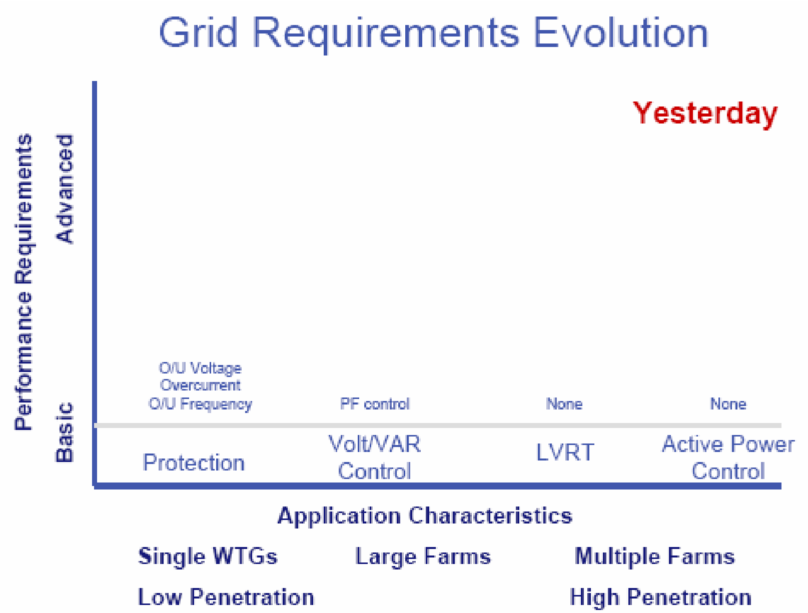
Increasing Penetration of Renewables

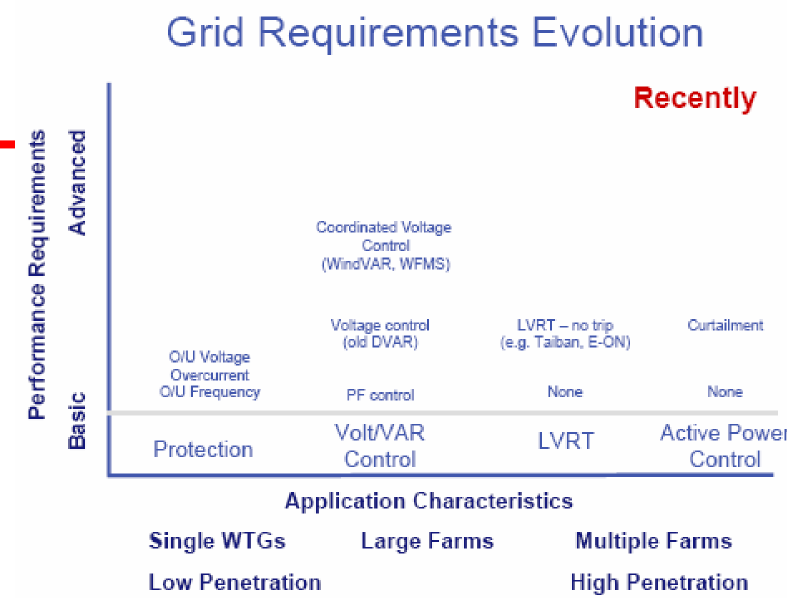


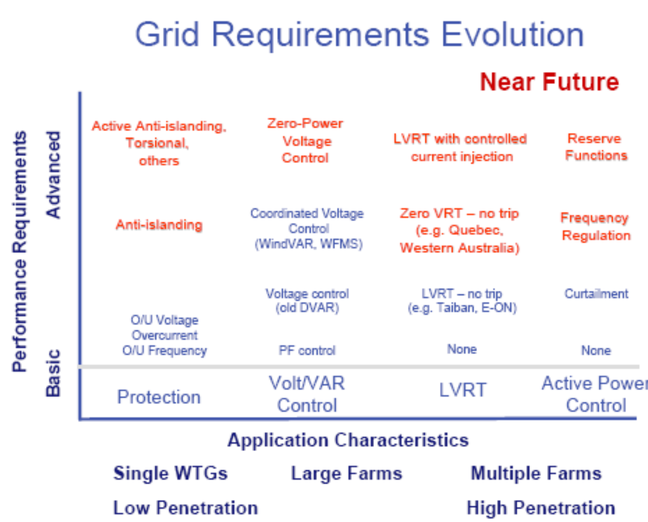
Denmark

- 14% of Electrical Energy
- New Control Regs.







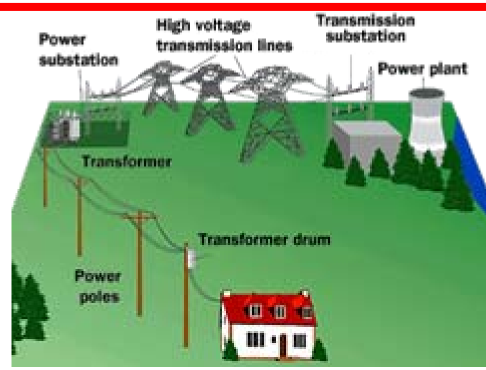


Harmonization?
Electronic Capability?

Power Distribution Options -- Battle

Thomas Edison and Joseph Swan

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



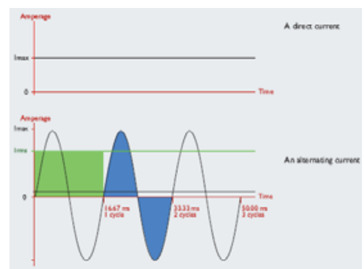
Move it at HV

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

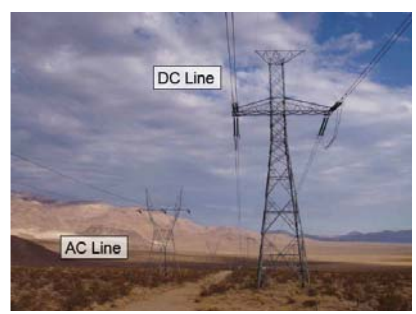
$$d = \sqrt{\frac{2\rho}{\omega\mu}}$$

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

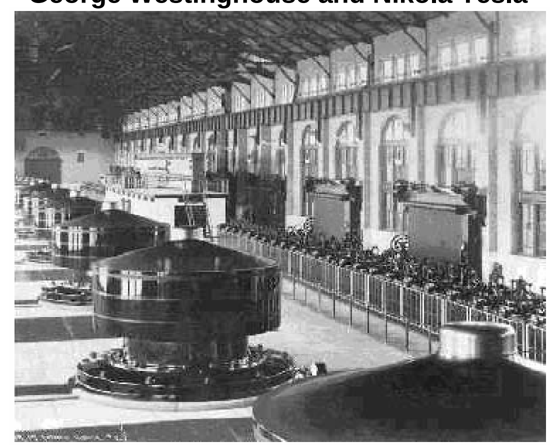
d or δ, 60Hz
Cu 8mm
Al 10mm
SiFe 0.1mm



Today, DC wins for T



George Westinghouse and Nikola Tesla



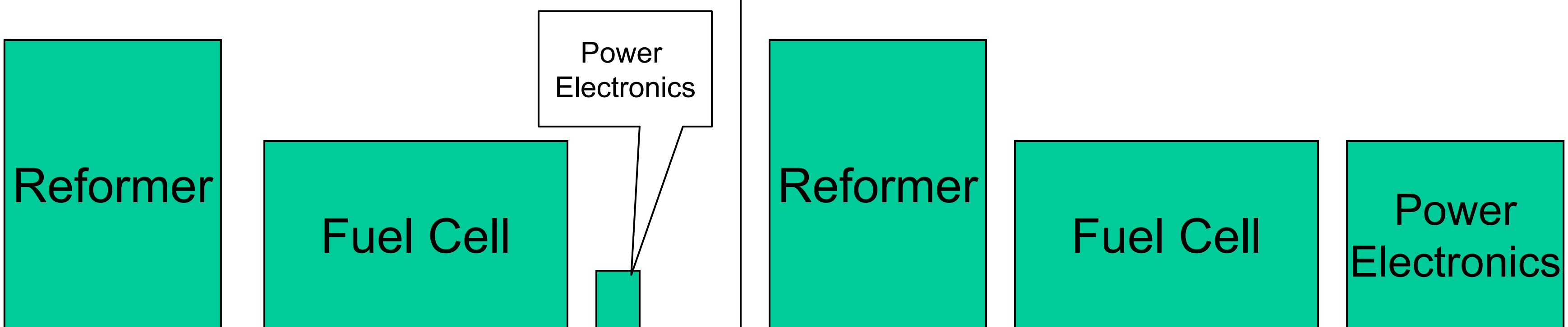
Adams Hydroelectric Plant
Niagara Falls 1895
Westinghouse, Tesla, Stanley

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

FC → dc/dc → HVDC ?

Power Electronics Can Provide the Solution - but at what cost?

Who is doing the System Design…?



The Vision

The Reality

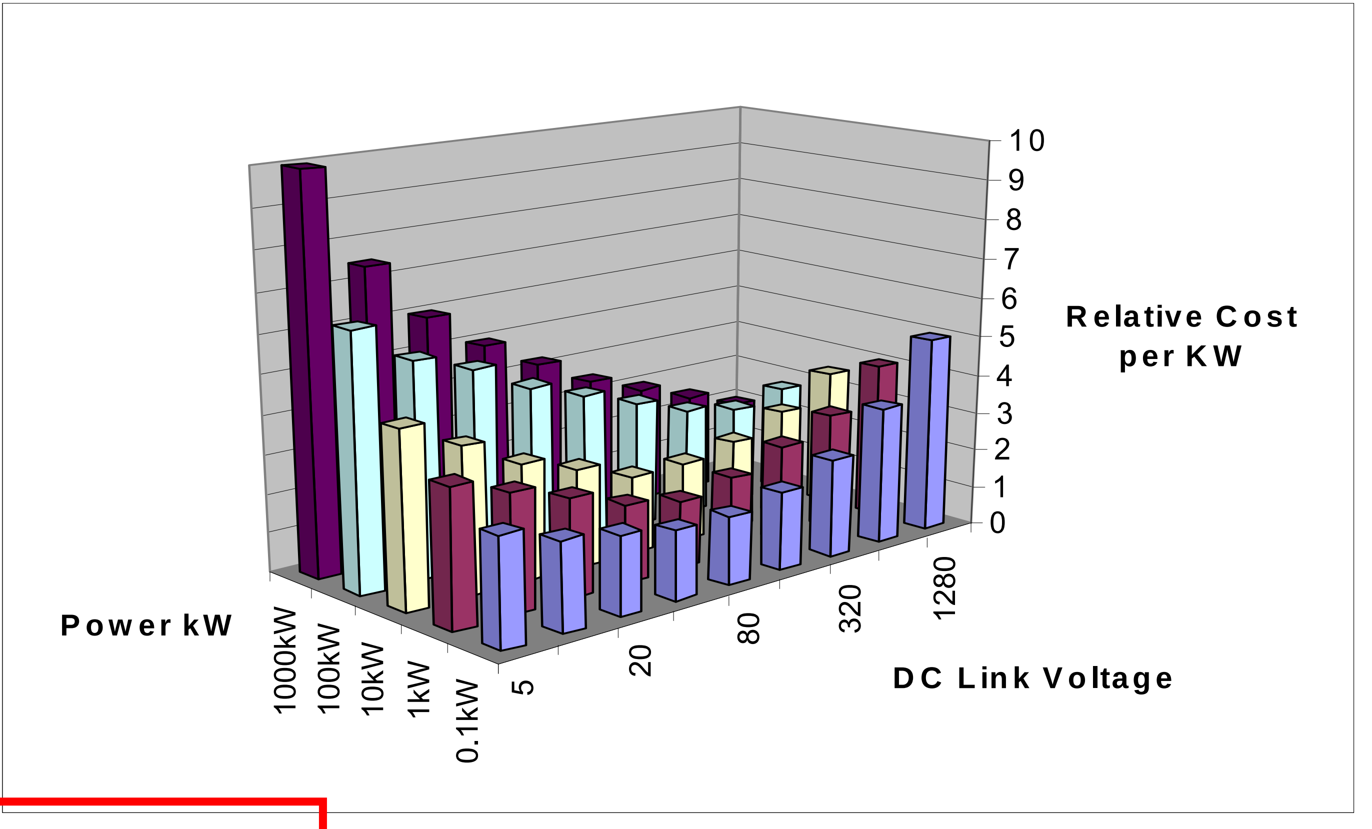
"Power Electronics is just a Commodity"

System Design and Specification are driving the Power Electronics Cost

FROM FC2000

Power Level and Circuit Topology define a balance of voltage and current that gives minimum cost

For a conceptual converter topology the curves might look like this:-



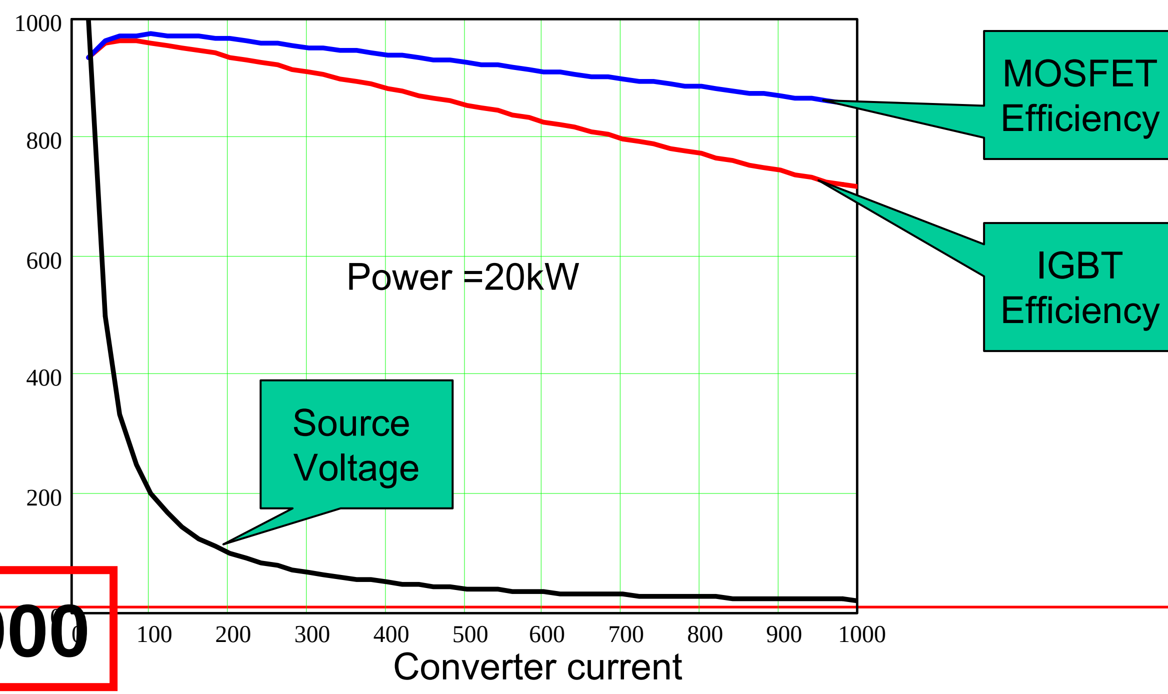
FROM FC2000

300V to 800V best for 10kW to 100kW power range, 800V and higher best for higher powers

Some general principles:-

Higher voltage semiconductor devices switch slower
Conversion frequencies must be lower at high voltages

High efficiency is difficult to achieve economically when power is the product of low voltage and high current



FROM FC2000

"Power Quality" is multi-dimensional – some attributes are more important to some users

- Necessary to meet load-specific power quality:
  - Harmonic content
  - Transient performance
  - Frequency tolerance
  - Load Circuit Protection
- Stand alone systems may not be required to beat/meet all utility characteristics
  - Saves components
  - Simplifies design
  - Reduces overall cost of system
- Smart Load and Non Invasive Load Monitoring
  - Intelligent control in place of grid imitation

FROM FC2000

Don't judge distributed power electronics $/kW costs based on motor drives

Motor drives are the most power dense and hence lowest $/kW of all DC/DC and DC/AC power conversion equipment - they have the lowest passive component count.

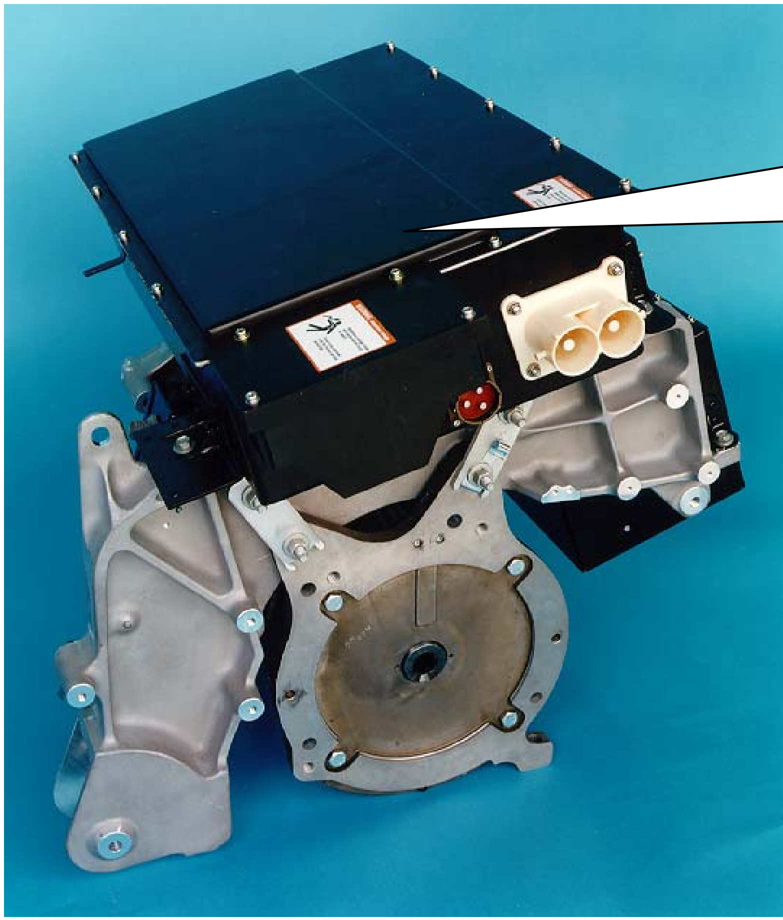
Typical numbers for very high power density designs:

DC/DC or DC/AC Power Converter	7kW/liter
DC/AC 3Φ Motor Drive	28kW/liter

In high volume production cost follows power density (& weight) so that cost expectation for DC/DC & DC/AC Power Converters should be 3 to 4 times the $/kW of motor drive converters.

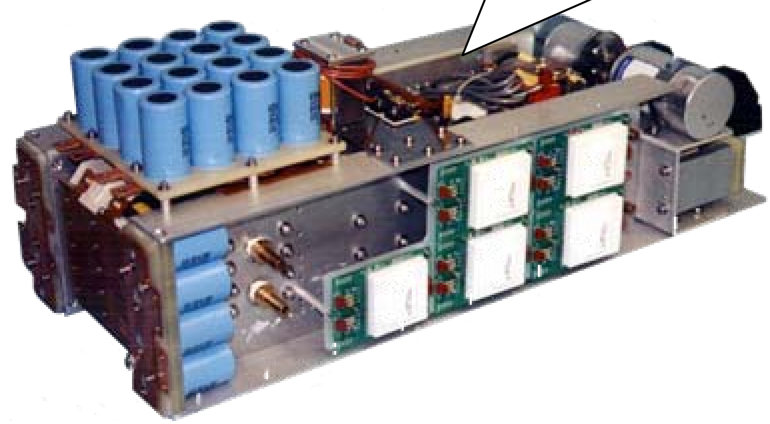
FROM FC2000

Hardware confirms the power density ratio



100kW motor drive inverter
1.3 ft^3, 56lb
DC input 320V

15kW Fuel Cell Converter
1.5 ft^3, 65lb
DC input 48V/48V



FROM FC2000

Big Inverters

- $200/kW?
- Extended Warranty?
- Performance?
- Research? -devices (SiC, GaN, … . Packaging, gate drives, control, passives, ….

  overload capability

  topology? Device dependent, say truly symmetric, bi-directional IGCT, 10kV+, building blocks, resonant transformers (isolation?), step-up to 25kV? CSI, …

Session 2a

Gordon

SIEMENS

DOE High-Megawatt Converter Technology Workshop

Tom Gordon,   January 24, 2007

DOE Integrated Coal Gasification Fuel Cell System with CO_2 Isolation

SIEMENS

A Multi-Year, Multi-Phase Cost Shared Program

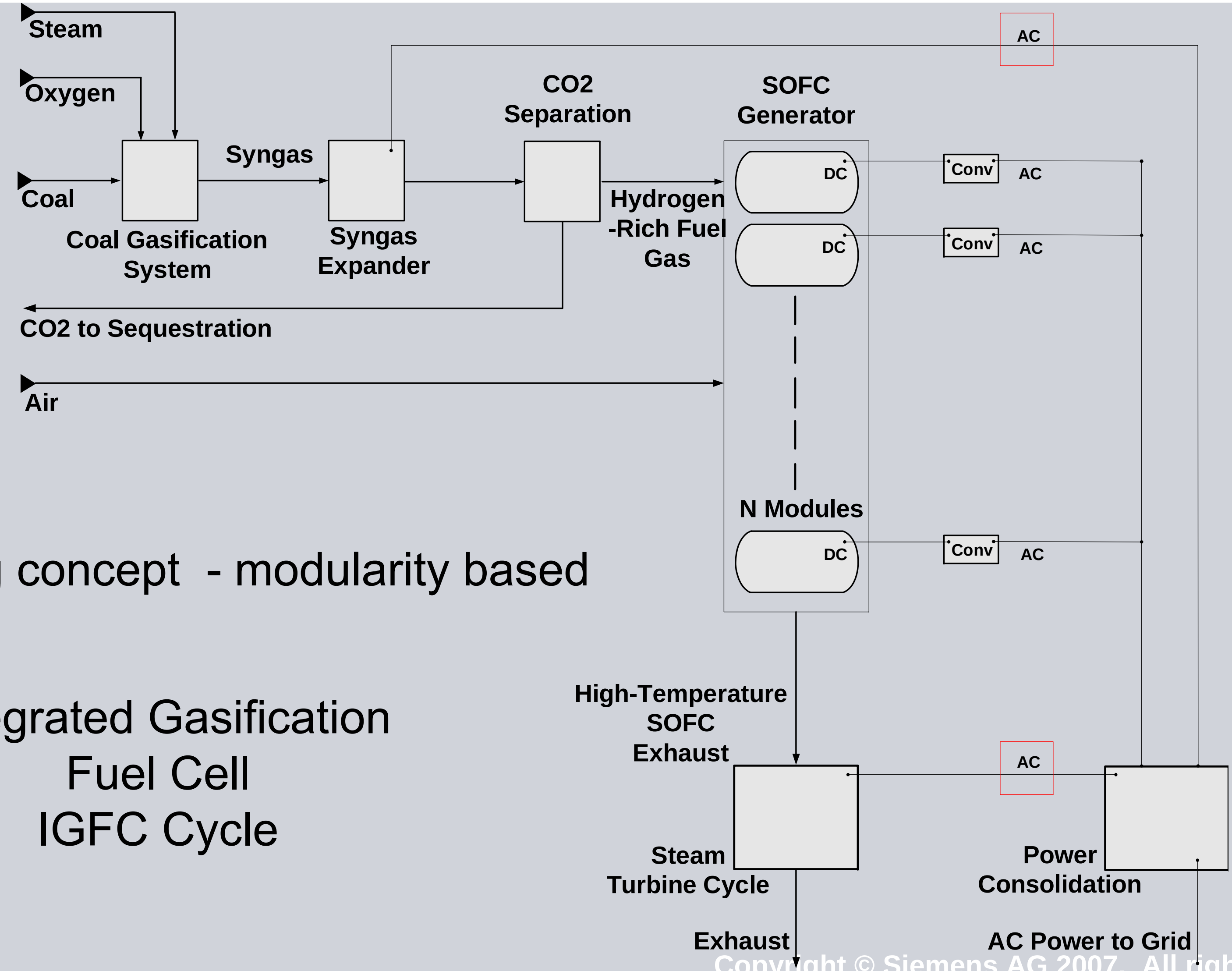
- Coal Syngas fueled, 100 MWe class fuel cell central station
- Efficiency > 50%, (based on HHV but excluding CO_2 Sequestration)
- 90% CO_2 Sequestration Potential
- $400/kWe (power island)

DOE Integrated Coal Gasification Fuel Cell System with CO_2 Isolation

Early concept - modularity based

DOE Integrated Coal Gasification Fuel Cell System with CO_2 Isolation

SIEMENS



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

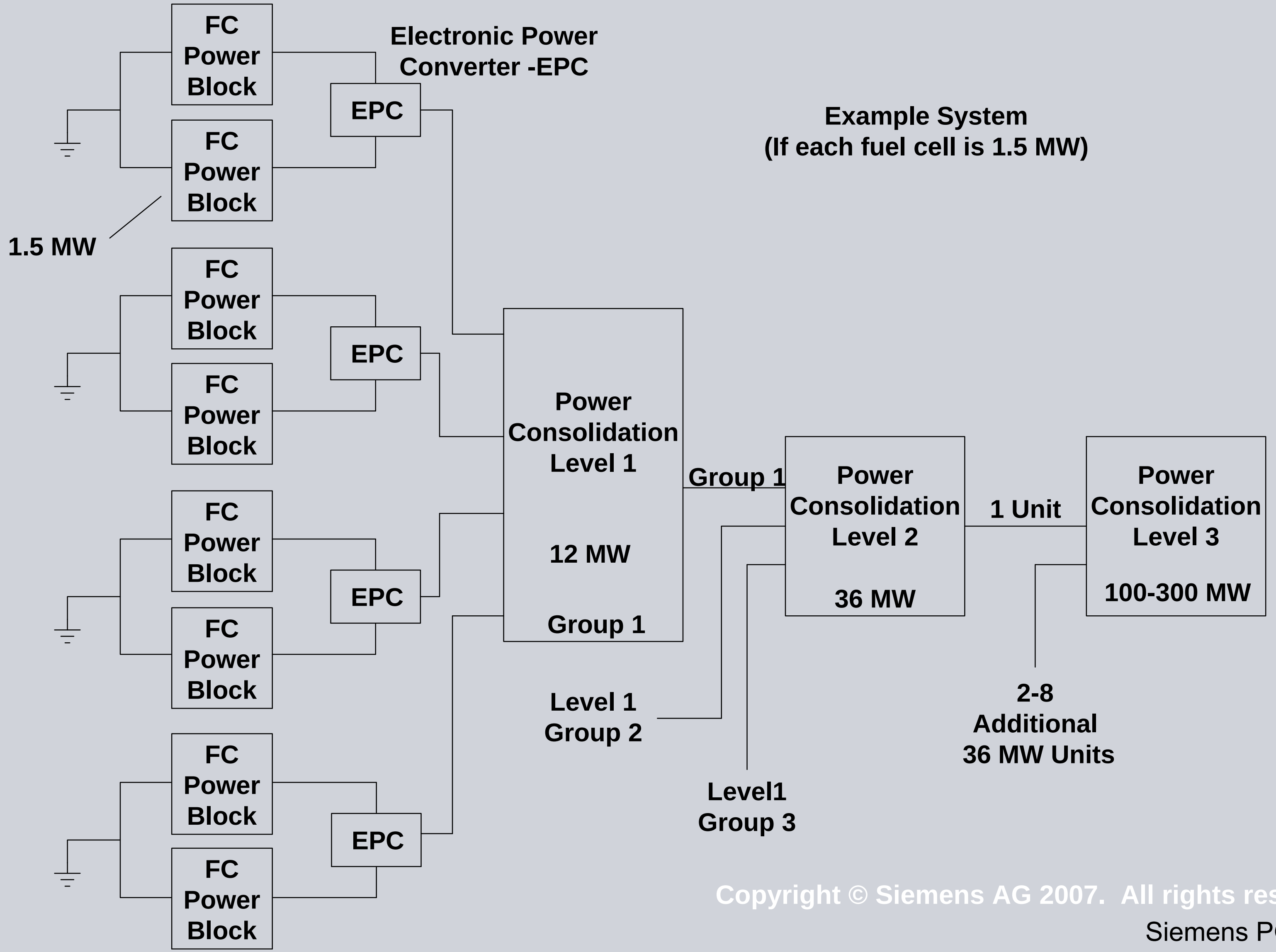
- **Fuel cells are a soft voltage source –poor terminal voltage regulation under load**
- **Present SOFC’s terminal voltage drop under fully loaded conditions may approach a ratio of nearly 2:1 vs. the maximum Vdc open circuit for the fuel cell**
- **SOFC modules for the IGFC system are expected to be 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

SIEMENS

- 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



Elements Needed

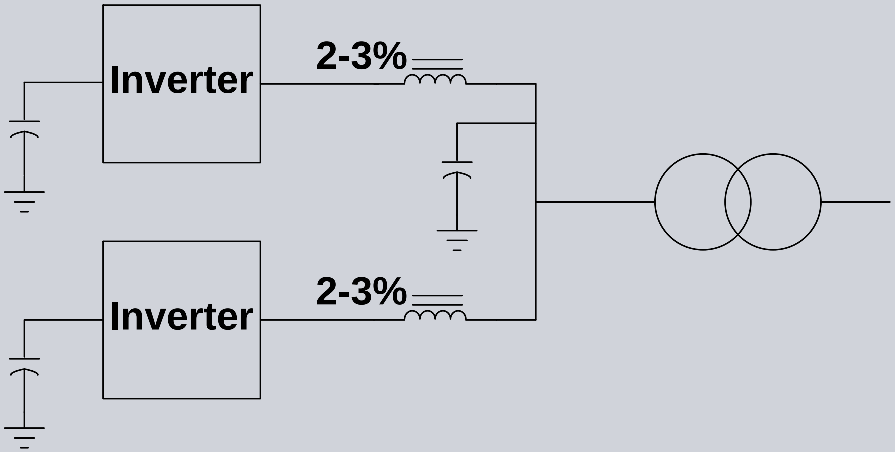
- High power/ modular/ cost efficient/ loading control circuit building block (EPC-electronic power converter)
- Modular EPC for 0.7 to 2 MW fuel cell module
- Performance optimized and cost efficient power consolidation methods
- Power consolidation can be either DC based (capacitors) or AC based (transformers)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

Some Issues Involved with Power Consolidation

SIEMENS

Issues Involved When Connecting Multiple Inverters from Separate DC LInks

If interconnection impedance ~5% then a 1% voltage error between any two inverters will give V/Z = 0.01/0.05 p.u. = 20% current flow

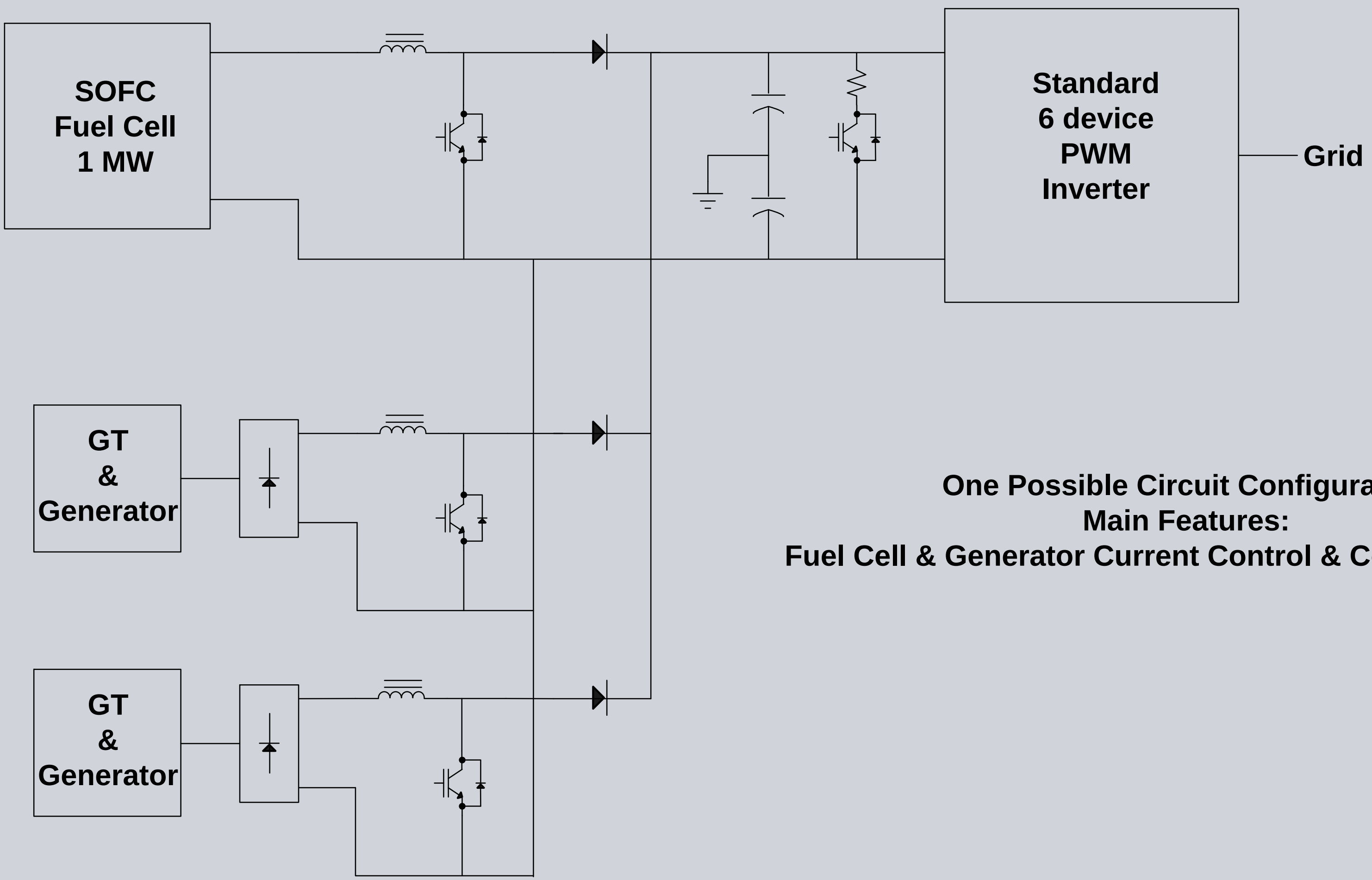


This corresponds to a 1% mismatch on the DC link or, a 0.6 degree phase reference error between the two inverter controllers

from Rolls-Royce Industrial Controls Presentation 18March99

Alternative Concept for Power Consolidation

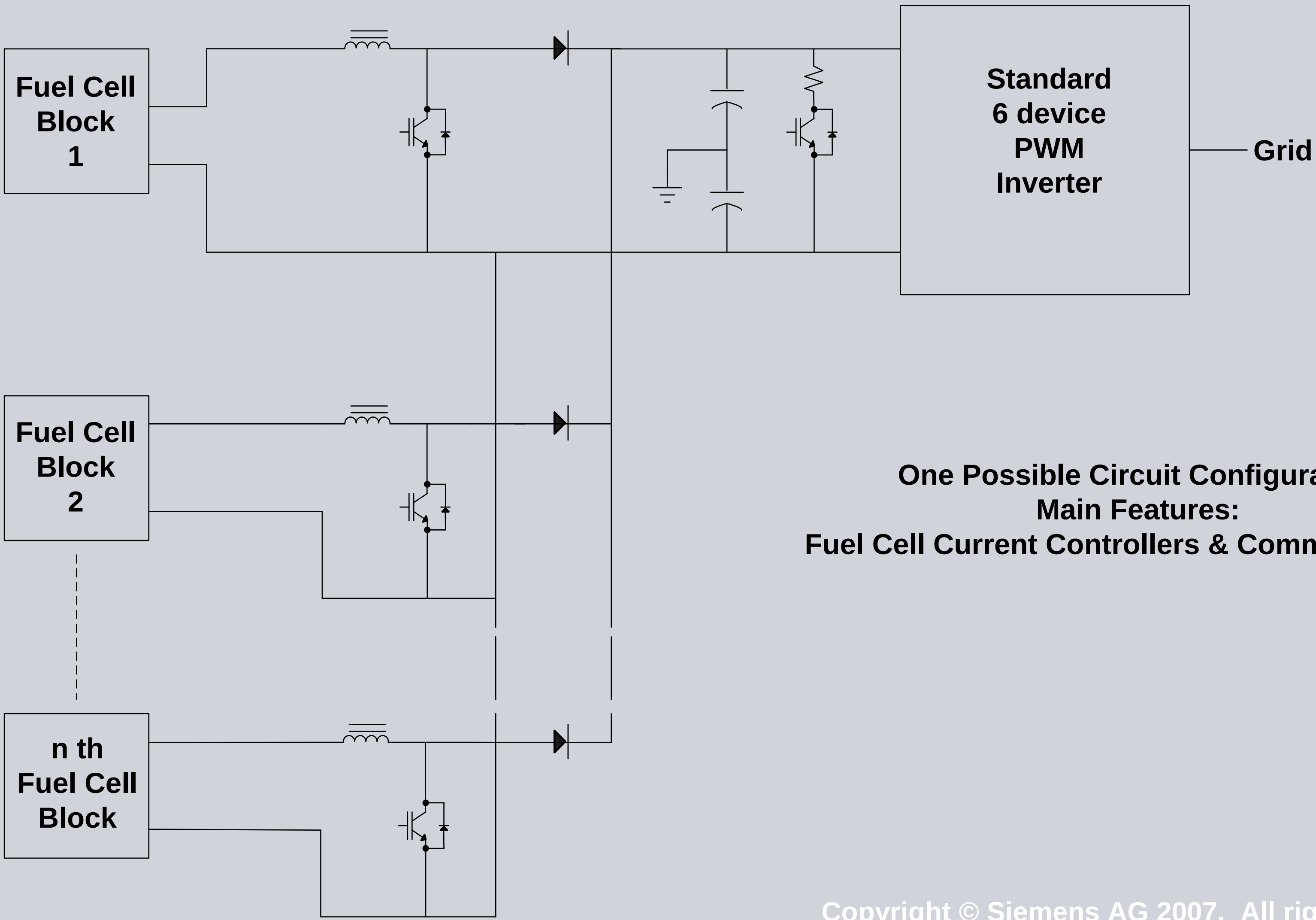
SIEMENS



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

from Rolls-Royce Industrial Controls Presentation 18March99

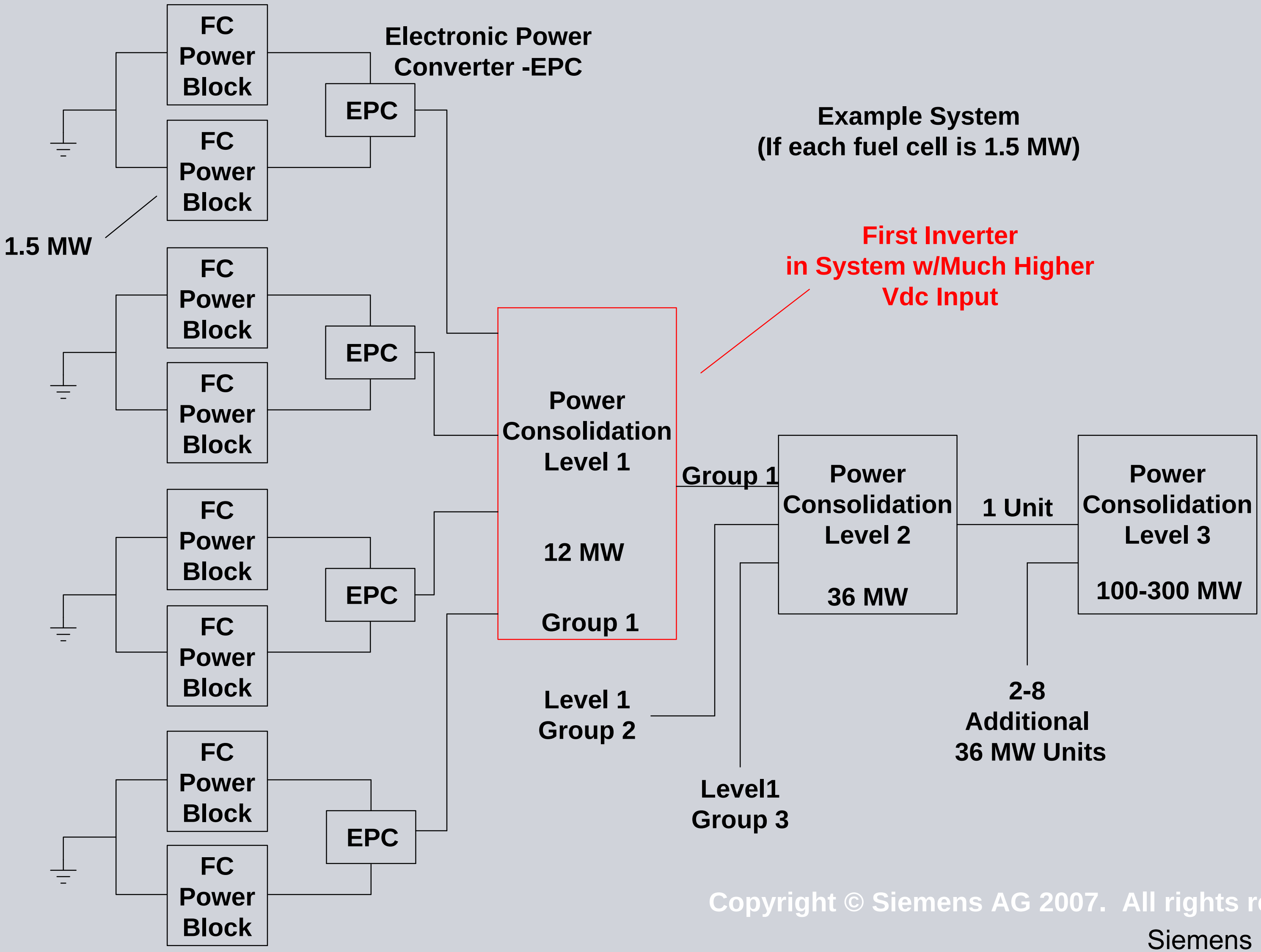
Concept Extended to Multiple Fuel Cells



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

Consolidation Possibility based on Previous Concept

SIEMENS



Siemens PG/SFC

Power Consolidation - Review

- Previous concept not necessarily preferred … it's an alternative with interesting advantages
- A disadvantage might be circuit protection at the lower stages since it would appear to be an all DC design (excepting a high frequency chopper transformer design approach to raise Vdc)
- With very limited samples we have seen chopper costs at about 1/8 total PCS costs when fully incorporated … higher if standalone
- The final target power level also drives design choices as the next slides address

Voltage & Power Sensitivity 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

Voltage & Power Sensitivity Check and Other Possible Approaches

SIEMENS

- 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 potential use of higher power multi-pulse stepped square wave inverters also should be considered

Voltage & Power Sensitivity Check and Other Possible Approaches

SIEMENS

- Multi-pulse stepped square wave inverter systems switch at line frequency not kHz frequency and use GTO (gate turn off thyristor) switches not IGBT switches
- GTOs have much higher power handling capability … cost advantages may exist by this approach
- Utility grade inverters use these devices and this method
- Applications include Static VAR Compensators (SVC), Flexible AC Transmission Systems (FACTS) and are built in the 100 – 500 MVA class

Modularity and Power Consolidation Review

- 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

Modularity and Power Consolidation
Review & Summary

SIEMENS

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

Modularity and Power Consolidation
Review & Summary

SIEMENS

- **One possible approach: conduct design exercises to determine a number of different circuits and system arrangements which can deliver the 100-300 megawatts to the grid**

Modularity and Power Consolidation
Review & Summary

SIEMENS

- From this initial study select three or four different approaches for much closer scrutiny
- Evaluate these on performance, availability, reliability, durability, redundancy strategies, cooling, fault tolerance, etc. … both at the modular level and at the 300 MW grid level … and which meet the various requirements for a modular design
- Gather costs (both existing & projected components) for the systems which meet the requirements and offer a durable and reliable design solution and then determine the $/kW question for the electrical conversion system

Session 2a

Tang

Olof Heyman

Technology Manager

ABB Grid Systems

Le Tang

ABB US Corporate Research
Raleigh, NC

Enhanced Power Reliability and Efficiency in new HVDC and FACTS development

ABB Power World
LEADERSHIP · TECHNOLOGY · PEOPLE
2007

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History and current HVDC & FACTS Technology

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World's first HVDC transmission, Gotland Sweden

Rating:

100 kV

20 MW

Cable type:

Mass-impregnated 1 x 90 mm^2 Cu

Length:

100 km

Year:

1954

HVDC & SVC development

Mercury Arc

Thyristor
Gen 1

Thyristor
Gen 2

Transistor
(IGBT)

Year

1954 | 1970 | 1980 | 2000

HVDC Technologies

600 MW, 200x120x22 meters

350 MW, 120x50x11 meters

HVDC Classic, Thyristor Technology

- Switched Reactive Power Control
- Typical design: valve building plus switchyard
- Overhead lines for long distance bulk power
- Mass impregnated cables for sea
- Back to Back

HVDC Light®, Voltage Source Technology

- Transistor (IGBT) controlled
- Continuous Reactive Power Control
- Dynamic voltage regulation
- Black start capability
- Typical design: all equipment (excluding transformers) in compact building
- Extruded cables suitable for undergrounding and sea

FACTS Technologies

Static Var Compensation (SVC)

- Thyristor controlled
- Reactive Power Compensation
- Increase of transmission line capacity
- Steady state voltage regulation
- Transient voltage support
- Power oscillation damping

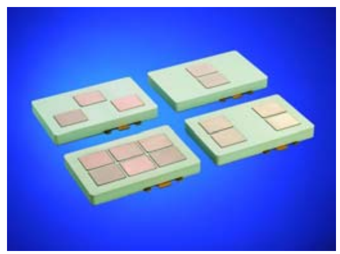
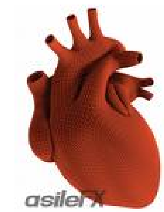
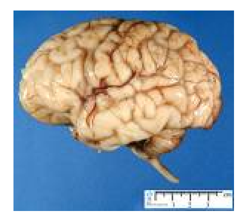
SVC Light (Statcom)

- Transistor (IGBT) controlled
- Flicker compensation
- Very fast response for load compensation

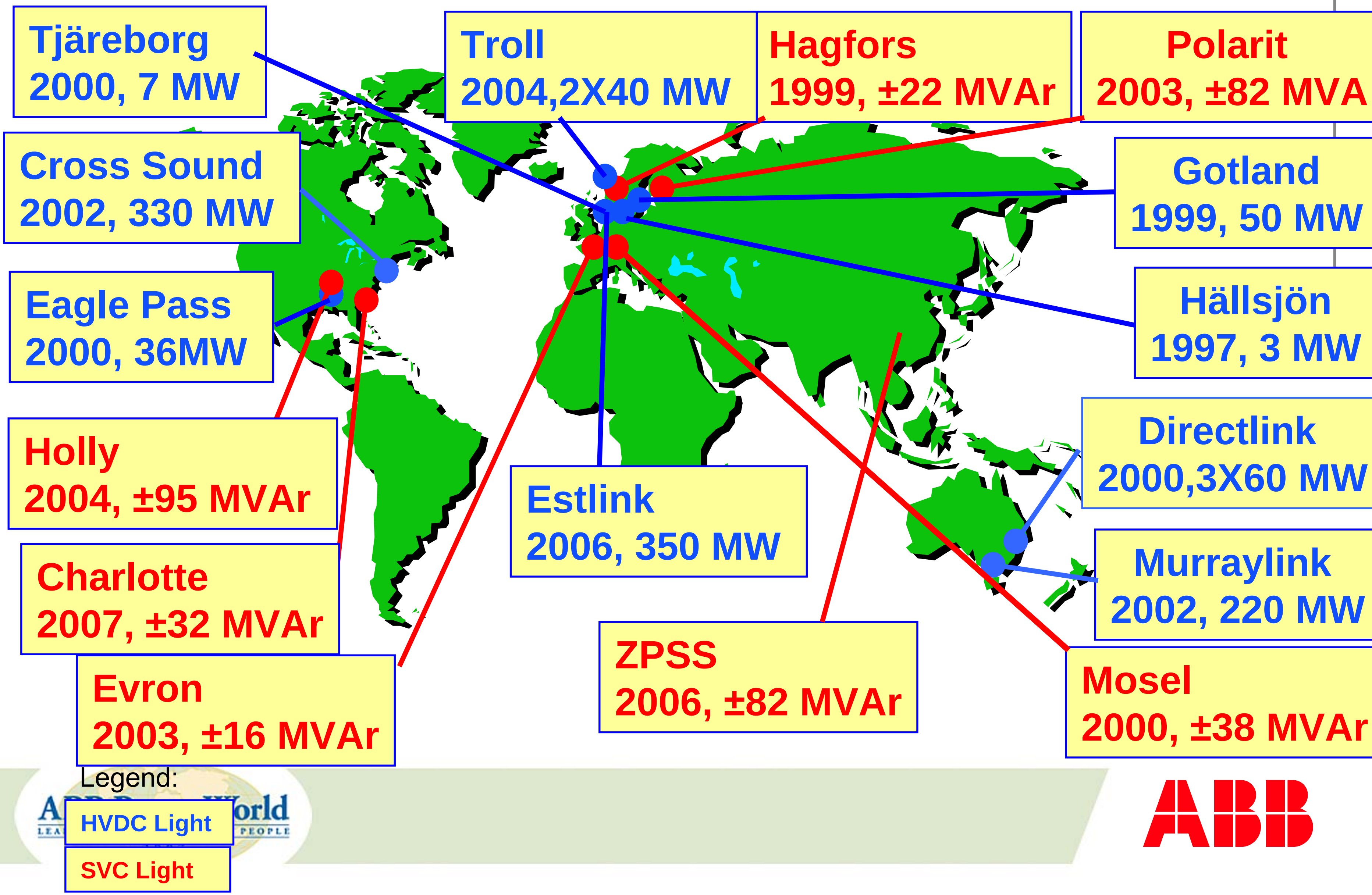
Series Compensation (SC)

- Increased transmission capacity
- Increased stability

HVDC and SVC, major building blocks

Classic	Light (Statcom)	
		Cable 
		Semiconductor 
		Control System 

Projects based on HVDC/SVC Light® Technology



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Next steps for Light Technology

Next step Light Concept

HVDC

DC Voltage	500 A	1000 A	1500 A
+/- 80 kV	98 MW	194 MW	296 MW
+-150 kV	185 MW	363 MW	555 MW
+/- 320 kV	350 MW	700 MW	1100 MW

Delivered technology

SVC

Voltage	500 A	1000 A	1500 A
36 kV			+/- 100 MVar

bles and Storage Integration

Power electronics

improve grid integration of

- Renewable generation
- Energy storage

Example

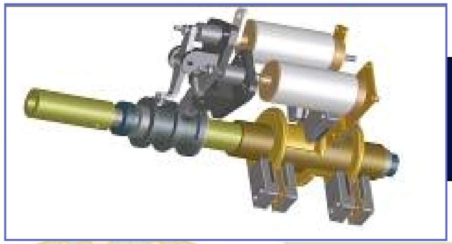
- GVEA, Alaska, backup for transmission system loss, win time to start up local generation
- Battery energy storage system (with Saft NiCd batteries) to deliver 27 MW for 15 minutes (up to 46 MW)
- Avoids running backup generation units in costly idle mode

ABB Core Technology Areas 2/2

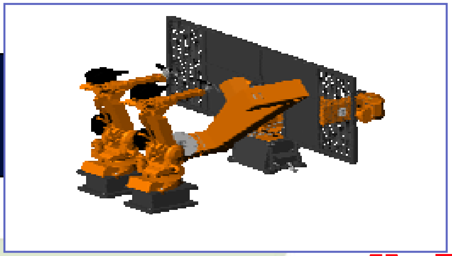
Insulation, limiting

Switching, breaking

Power electronics

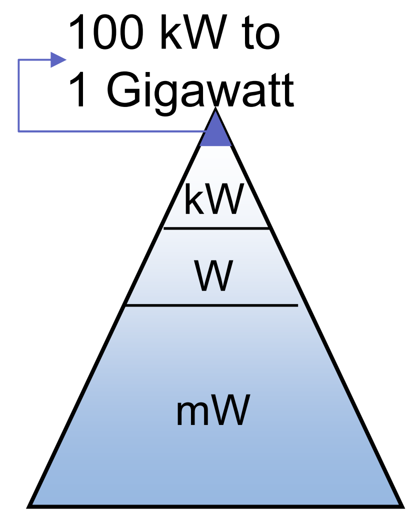


Mechatronics



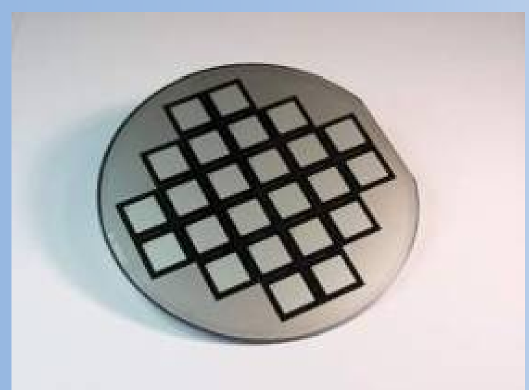
Core component: semiconductors

- ABB power semiconductor factory in Lenzburg, Switzerland
- Class 10 Cleanroom ***(500 times cleaner than a surgery room)***
- Ensures highest reliability of system operations



Production:

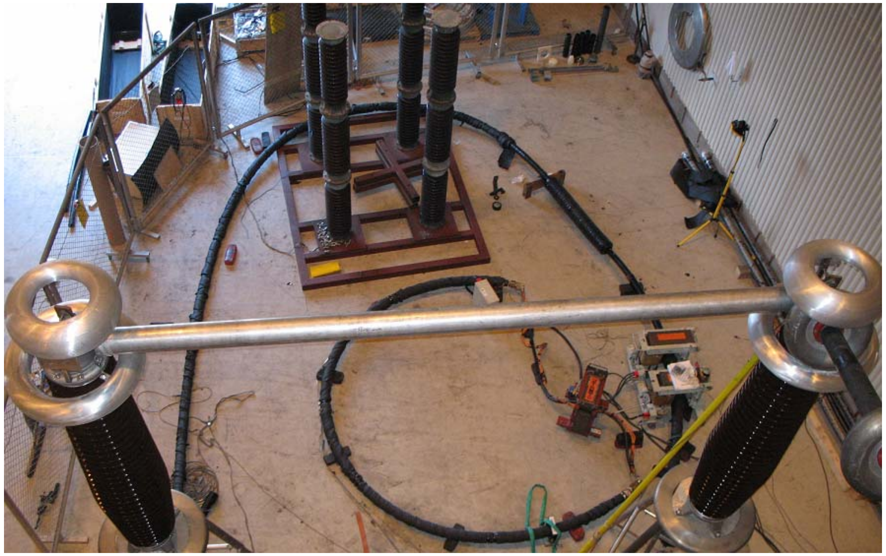
Product:



Troll application:

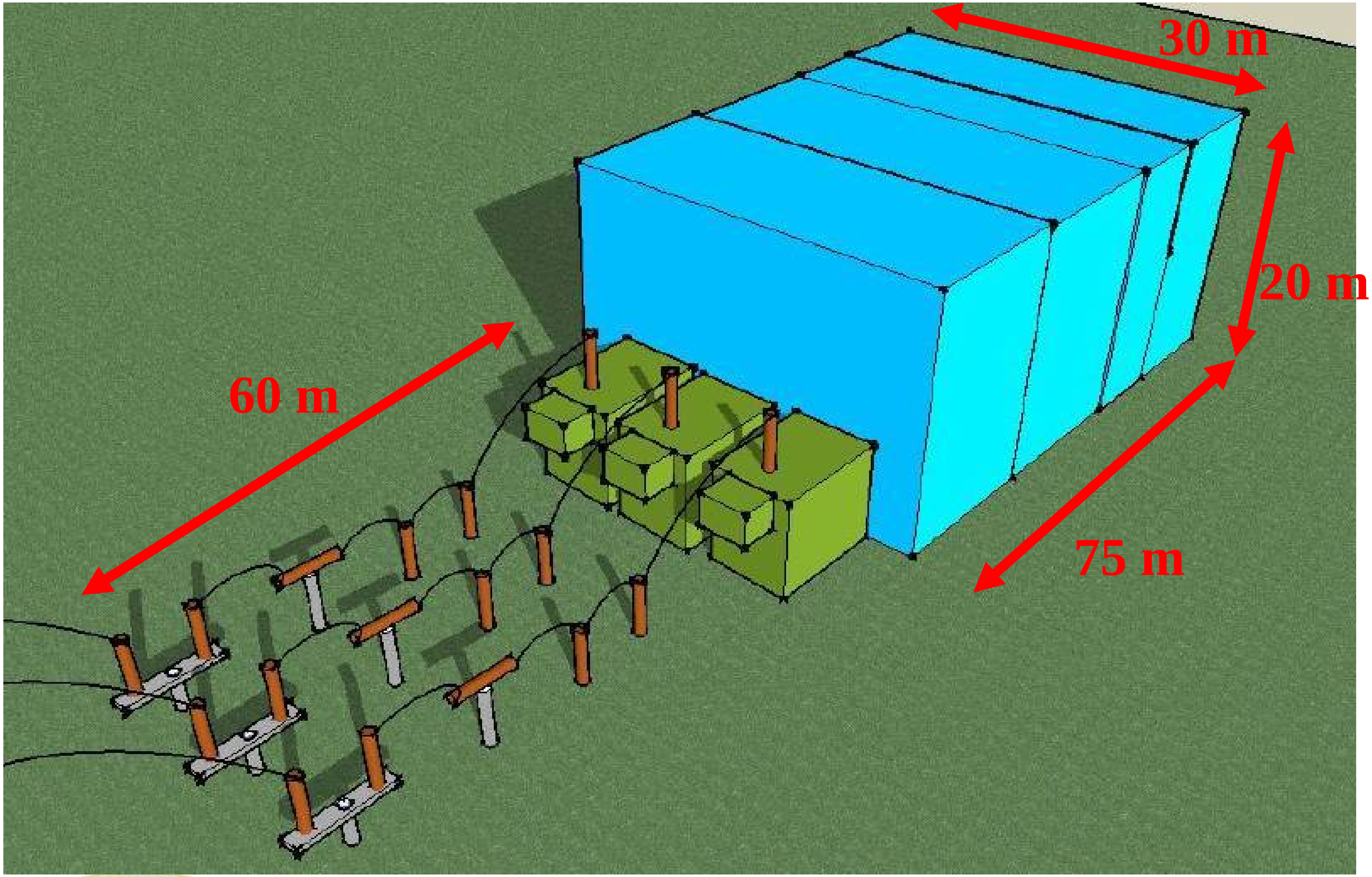
ABB

Cable system development



- Voltage: 150 → 320 [kV DC]
- Full type test, 30 days at 600 kV
- Completed Q4 2006

Layout for 320 kV, 350-1100 MW, Converter station



Reliability and efficiency for Light Technology

Proven offshore technology Troll A and Valhall

Customer's need

- Provide power to new compressors and at the same time minimize emission of CO_2 and the overall cost

ABB's response

- Turnkey 2x40 MW ±60 kV HVDC Light® offshore transmission system with high voltage Motorformer

Customer's benefits

- Compact and low weight design reduces investments on platform
- Reliable power supply

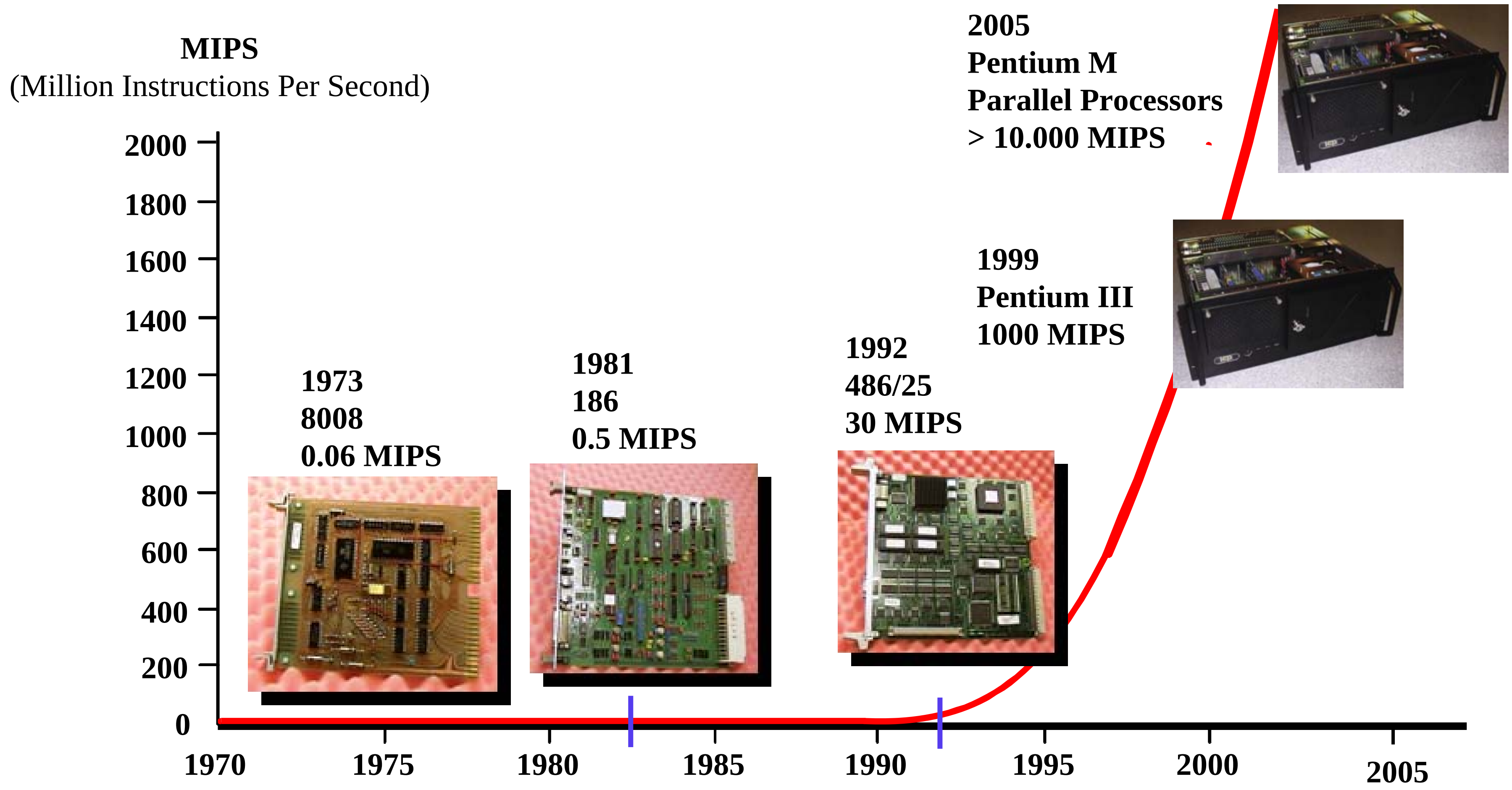
Offshore power supply, performance driver

- **Increased reliability**
  - Forced Outage Rate 5/year → 2/year → 1/year
- **Increased availability**
  - Maintenance intervals 1/year → 1/2years → 1/5years
- **Reduced start-up time**
  - Commissioning time month → weeks → days

Summary for Light reliability

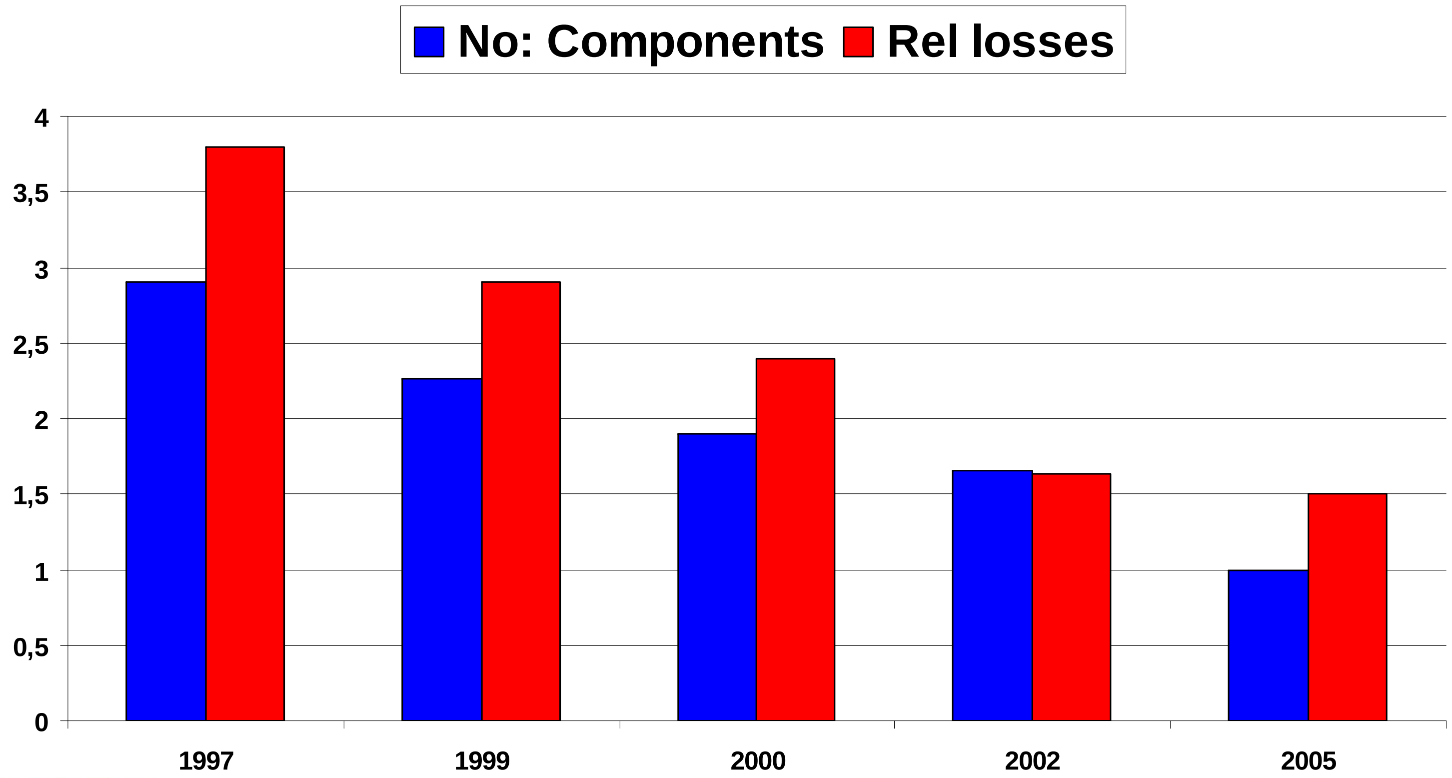
- Achievements so far in existing plants
  - Calculated number of outages / year have been reduced from 5 to ~ 2
  - Calculated availability has been increased from 96% to 98.5%
  - Further improvements are expected and have also been observed in existing plants
- “Best in class” existing plants
  - In Troll we have to date 4 converter years with zero outages and 100% availability. This is particularly extraordinary since this is achieved in the first year of operation.
  - In Cross Sound Cable we have 1 outage the last 12 calendar month (2 converter years) after completed implementation of improvement package.

Development computerized C&P



IGBT/Control development HVDC Light®

- Number of components reduced 65% since 1997
- IGBT Voltage constant 2.5 kV
- Losses reduced 60% since 1997



Long distance Bulk Power Transmission

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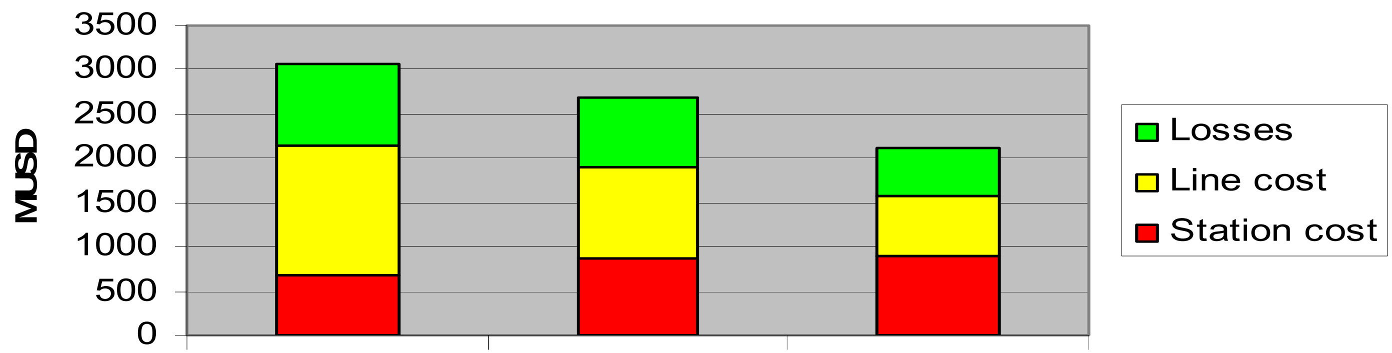
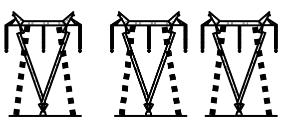
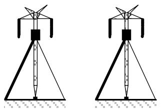
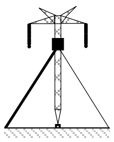
800 kV DC for long distance bulk power transmission



	765 kV AC	500 kV DC	800 kV DC
Number of lines:			
Right of way (meter)	~300	~ 120	~ 90

800 kV DC for long distance bulk power transmission

- 800 kV Classic DC with OHL
- Transmission capability: 6400 – 9000 MW

Summery

- HVDC&FACTS made for efficiency and reliability
  - Efficient transmission
  - Stabilizing networks
  - Lower losses

- HVDC&FACTS new development adds to efficiency and reliability
  - Light Technology; a standardized way with high reliability
  - 800 kV DC; A new rating for higher efficiency

ABB

Session 2b

Hingorani

High-Megawatt Converter Technology Workshop

DOE Office of Clean Power Systems,
U.S. Army Construction Engineering Research and Development Center (ERDC), and
National Institute of Standards and Technology (NIST)

January 24, 2007, 8:00 AM -5:00 PM

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High MW Power Electronics - Areas of Applications

Generation
Wind Farms
Fuel Cell
Variable Speed Hydro

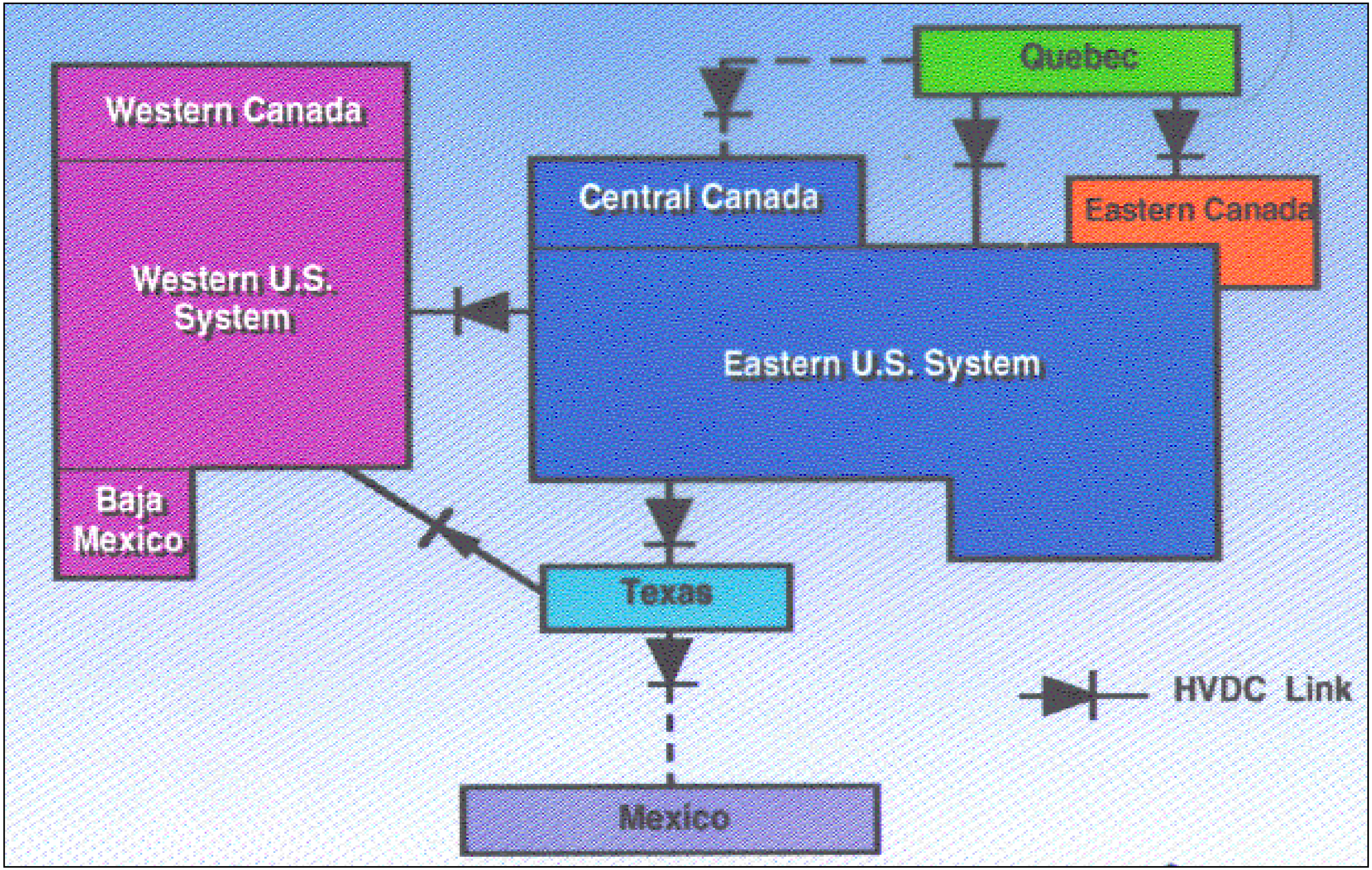
Transmission
HVDC Transmission
FACTS

Distribution
Custom Power

Storage
Battery
Flywheel
Super Capacitor
Superconducting-Magnet

Industrial
Variable Speed Drives
Rail Transportation
Ships

Military
Ship Propulsion
Aircraft Launch
Weapons
Bases



North America AC Power Systems and HVDC Interconnections

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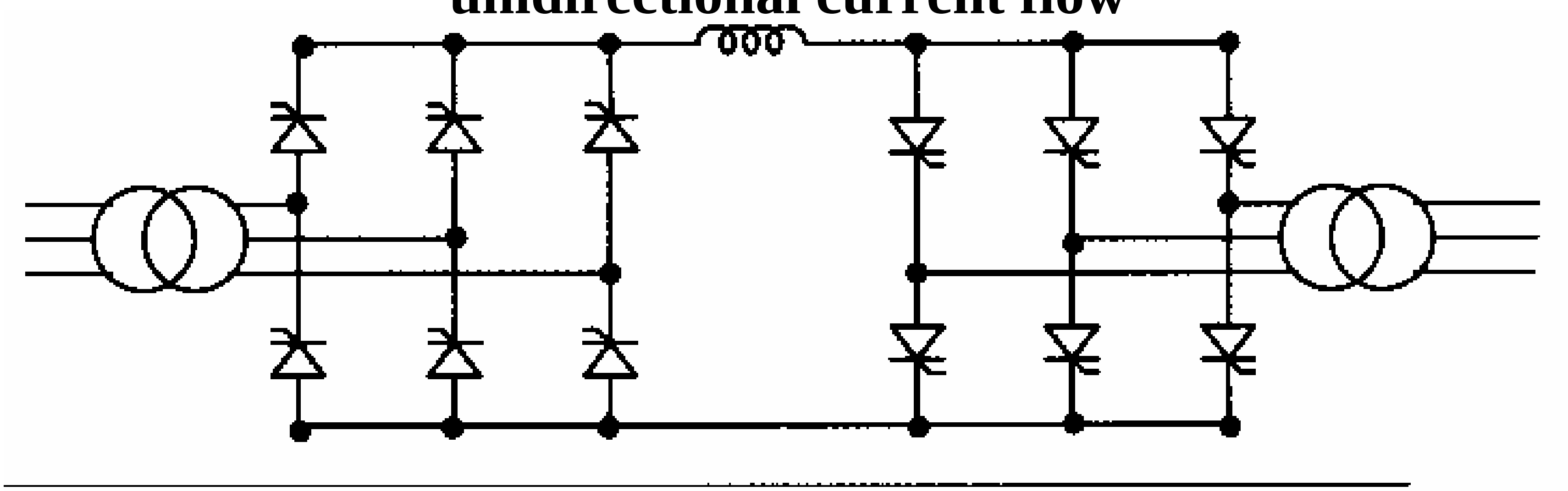
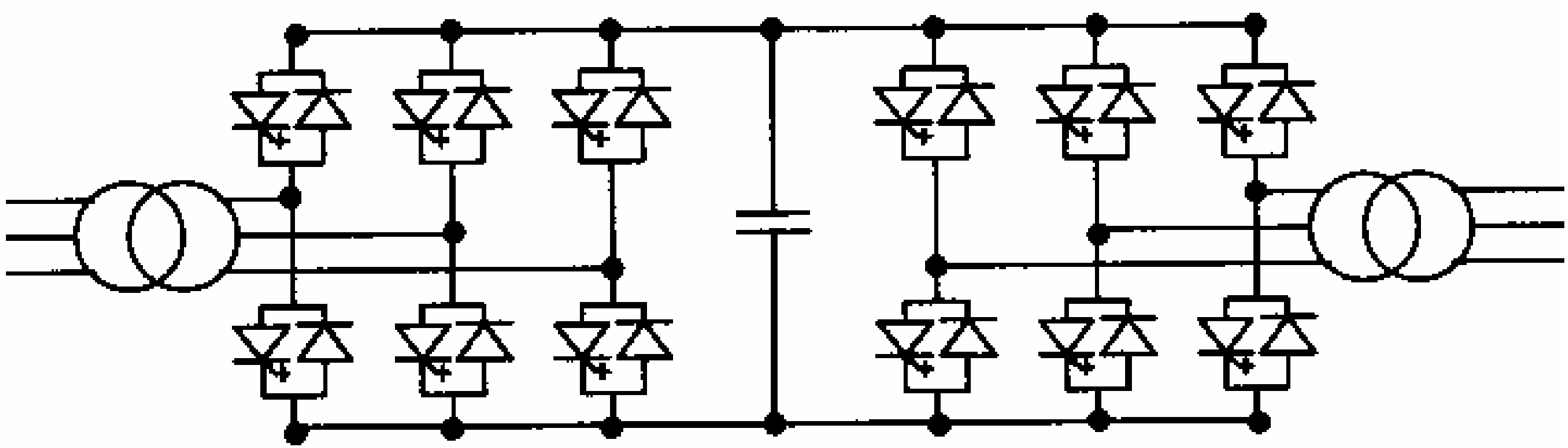
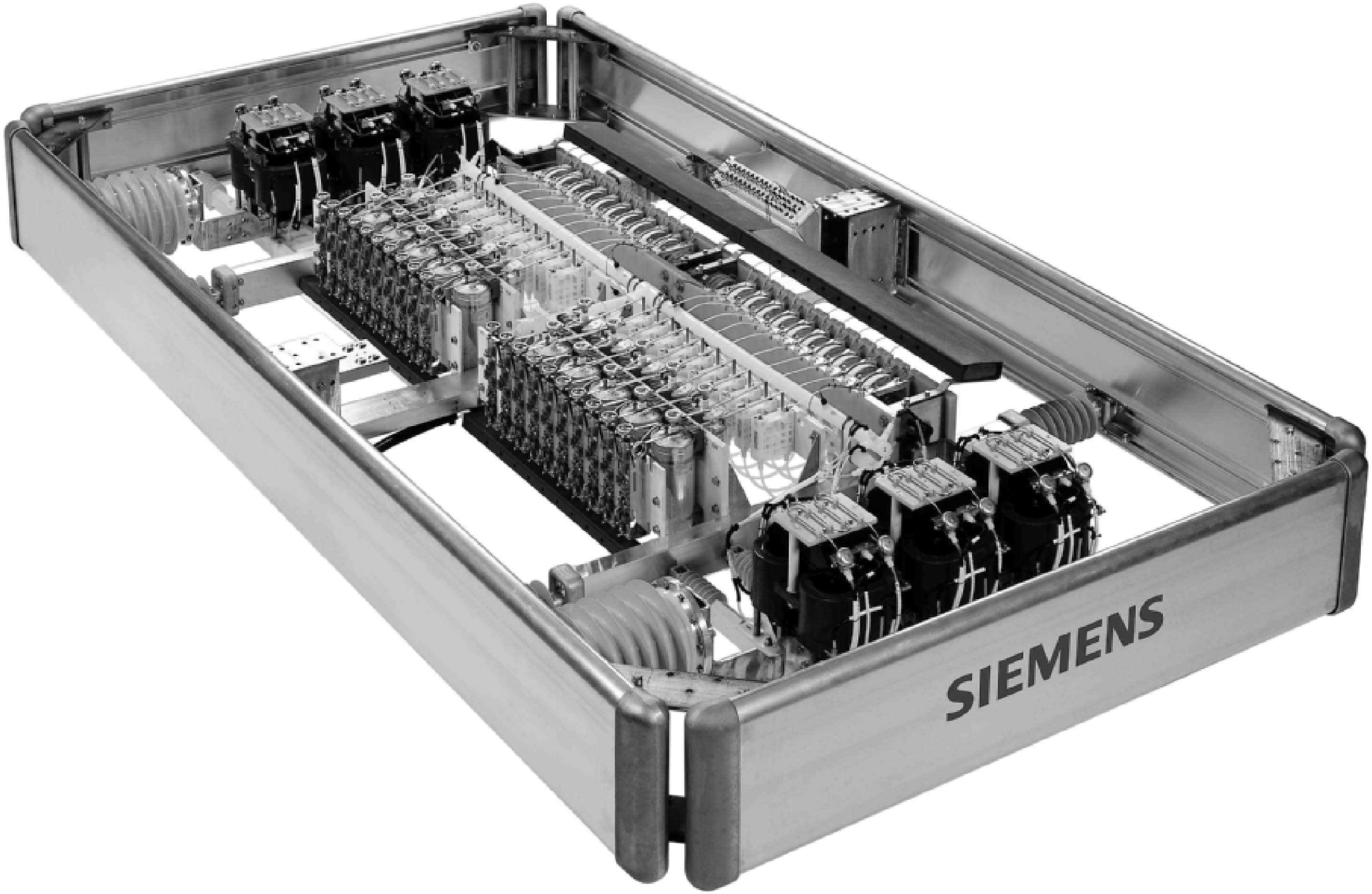
Current Sourced Converter System, which requires unidirectional current flow



Voltage Sourced Converter System which requires unidirectional dc voltage

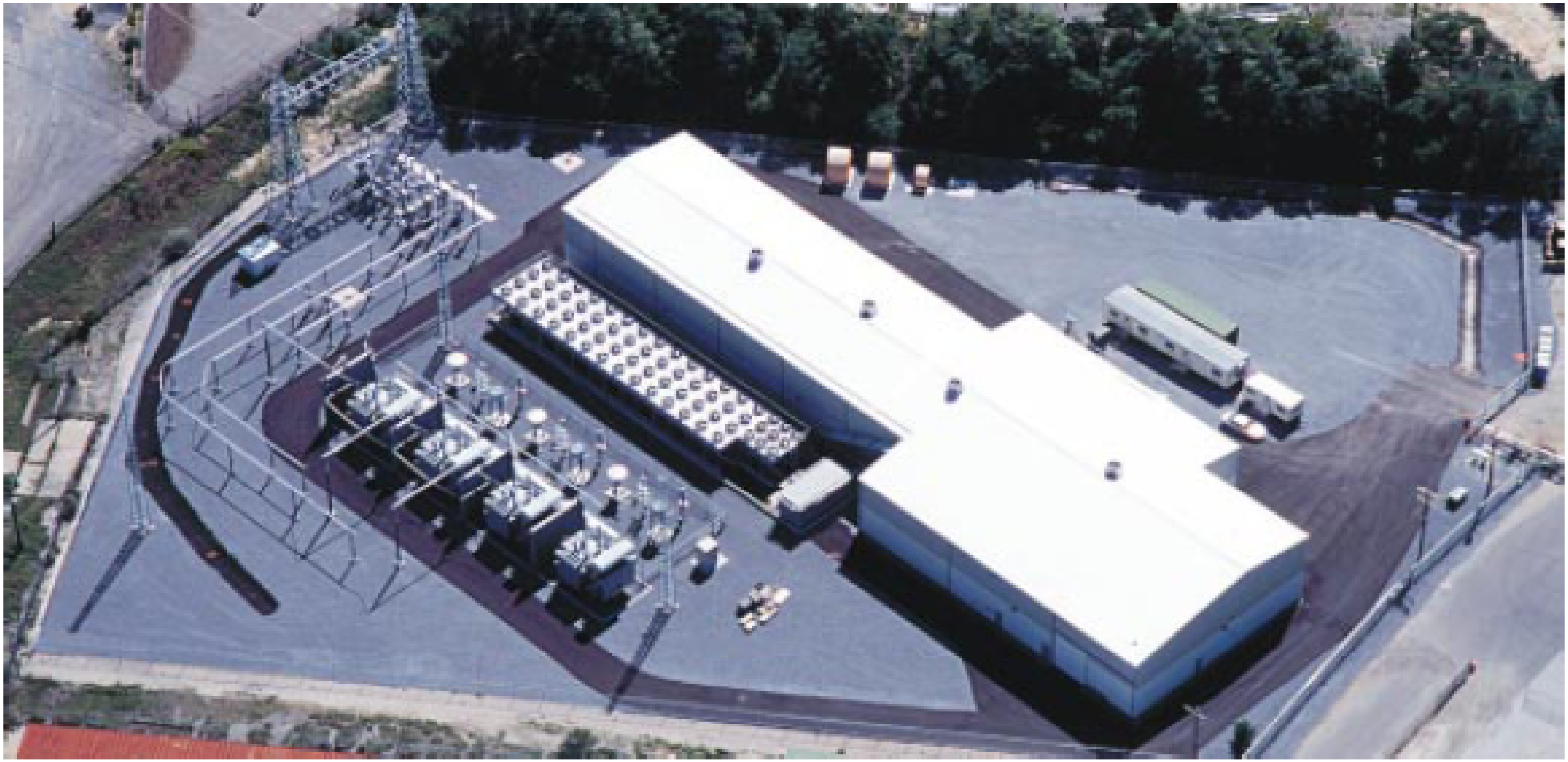


Suspended Thyristor Based Quadruple Valves making a 12-Pulse Converter rated 500kV (Pacific DC Intertie) (Siemens)



Building block for HVDC application including up-to thirty series Thyristor levels (Siemens).

Cross Sound Cable Interconnector
Connecticut and Long Island, USA



Converter Station at Shoreham. 330MW. + -150kV.
80m x 25m x 11m (ABB)

ABB

Constraints on Useable Transmission Capacity – FACTS

System Dynamics:

Transient and Dynamic Stability
Subsynchronous Oscillations
Dynamic Overvoltages and Undervoltages
Voltage Collapse
Frequency Collapse

System Steady State:

Uneven Power Flow
Excess Reactive Power Flows

Natural Limits

Insulation Voltage Capability
Conductor Thermal Capability

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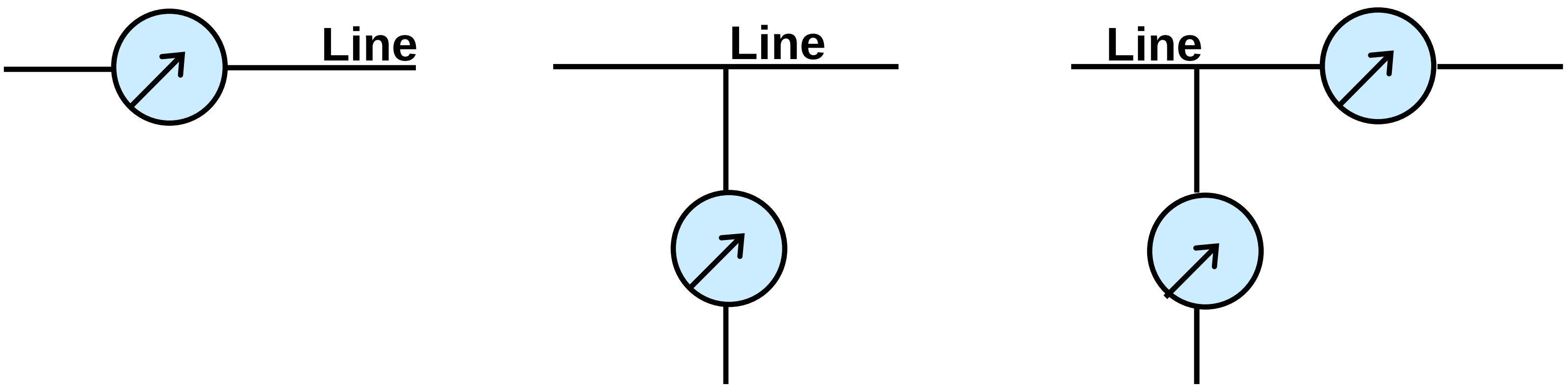
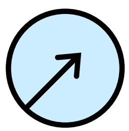
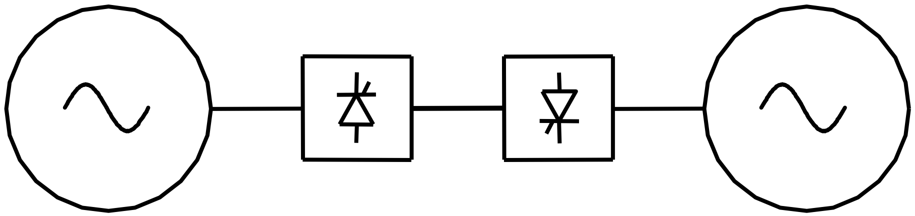
FACTS and Custom Power Concepts





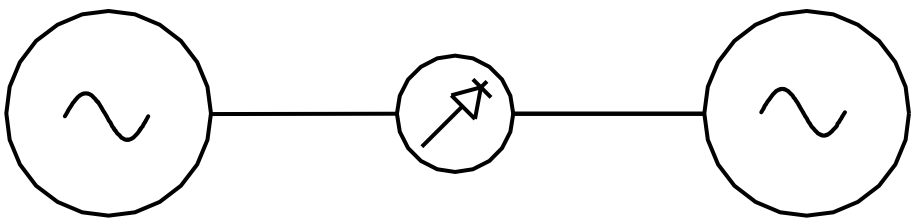
- May be active static switch or impedance converter or a combination thereof.
- When in shunt, cause current injection into the line, and when in series, causes voltage injection in series with the line.

HVDC and FACTS: Complementary Solutions



HVDC:

- Power control, voltage control, stability control
- Independent frequency and control



FACTS:

- Power control, voltage control, stability control

Installed Costs (million of dollars)

Throughput MW	HVDC 2 Terminals	FACTS
200 MW	$M 40-50	$M 5-10
500 MW	75-100	10-20
1000 MW	120-170	20-30
2000 MW	200-300	30-50

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Kayenta TCSC

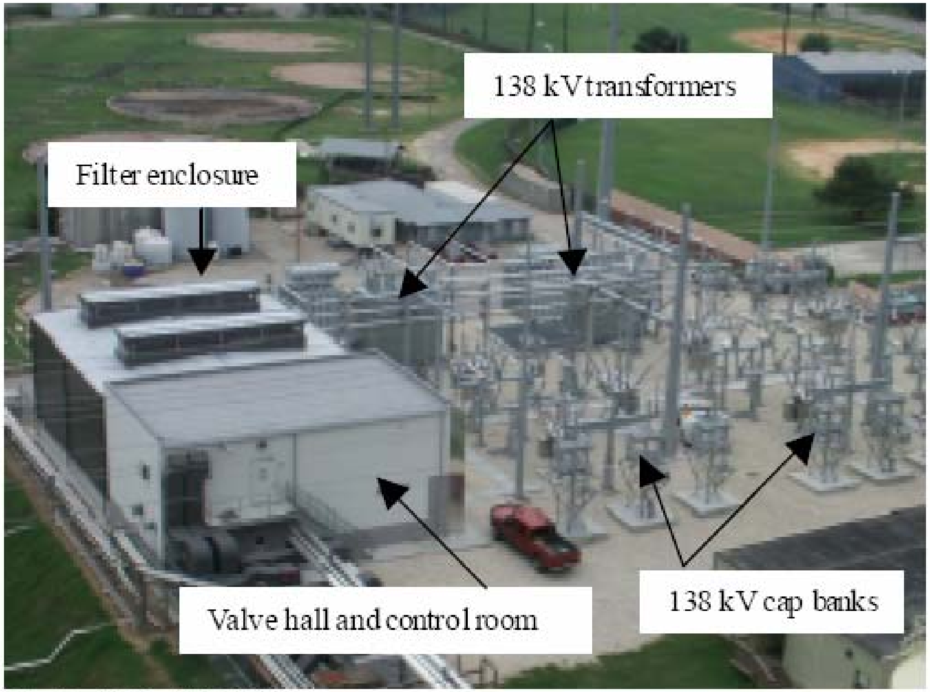


Fig. 3. Holly STATCOM

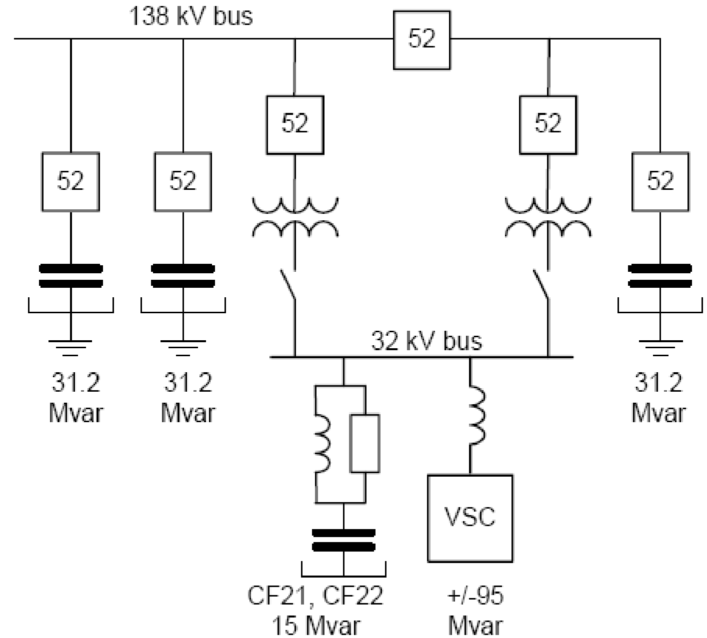


Fig. 1. Holly STATCOM single line diagram.

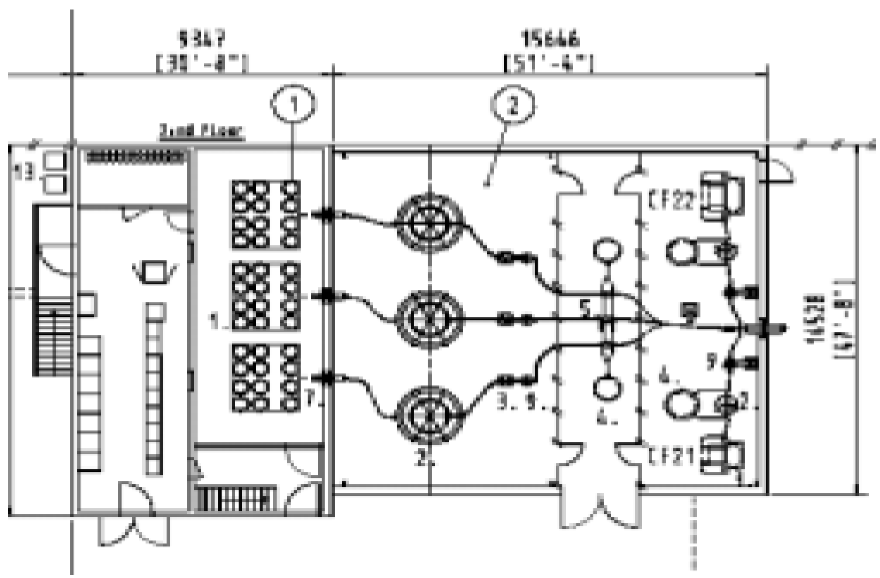
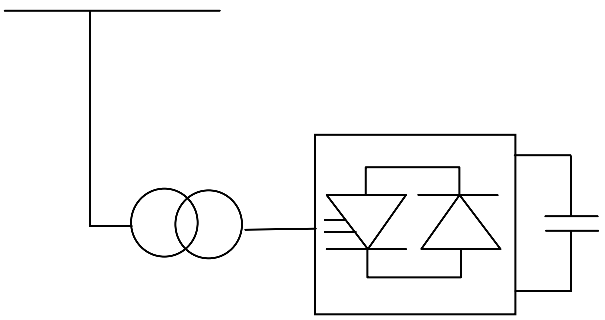
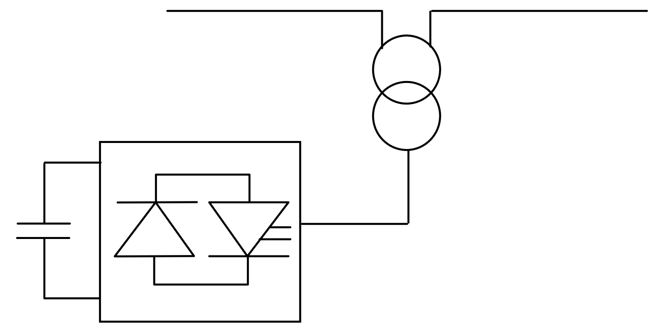


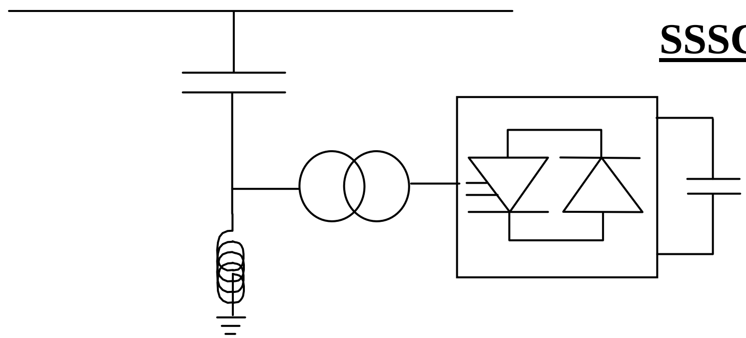
Fig. 2. Holly STATCOM layout
1) Valve hall
2) Enclosed 32 kV equipment



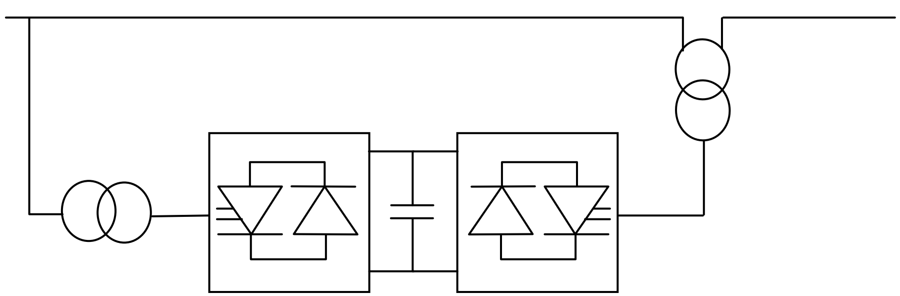
STATCOM



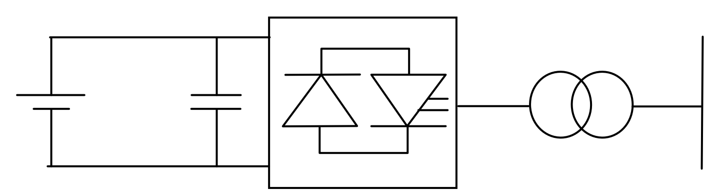
SSSC



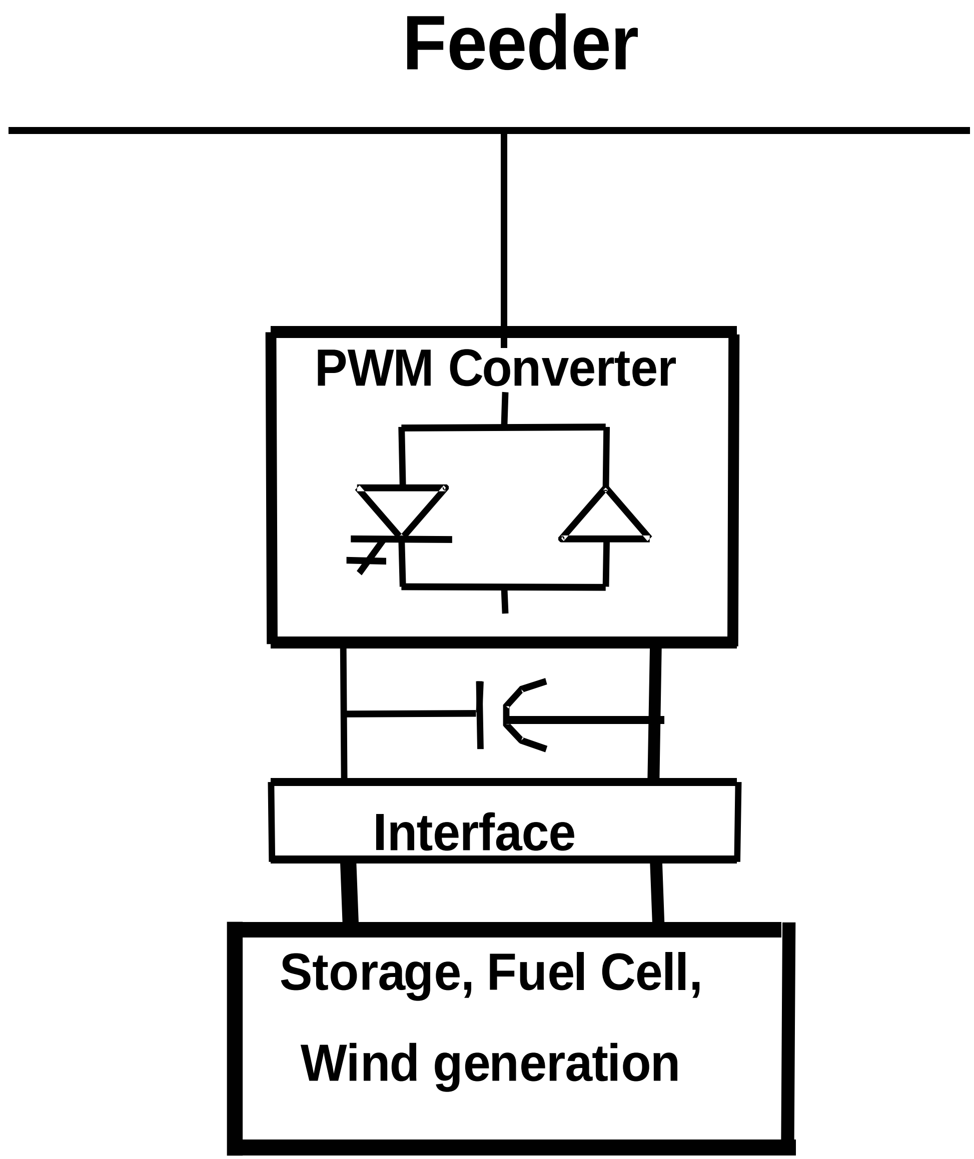
Active filter



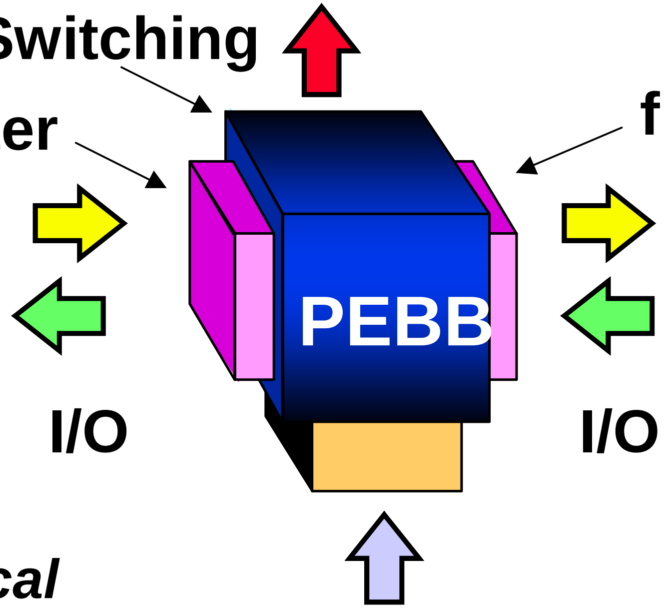
UPFC



Energy Storage


Feeder
PWM Converter
Interface
Storage, Fuel Cell,
Wind generation

* PEBB defined by IEEE
(Power Engineering Society)



Senses what they are plugged into...

Senses what is plugged into them...

Makes the electrical conversion needed via software programming

Functions In Software
Inverter
Breakers
Frequency Converter
Motor Controller
Power Supply
Actuator Controller

Like a child’s set of blocks

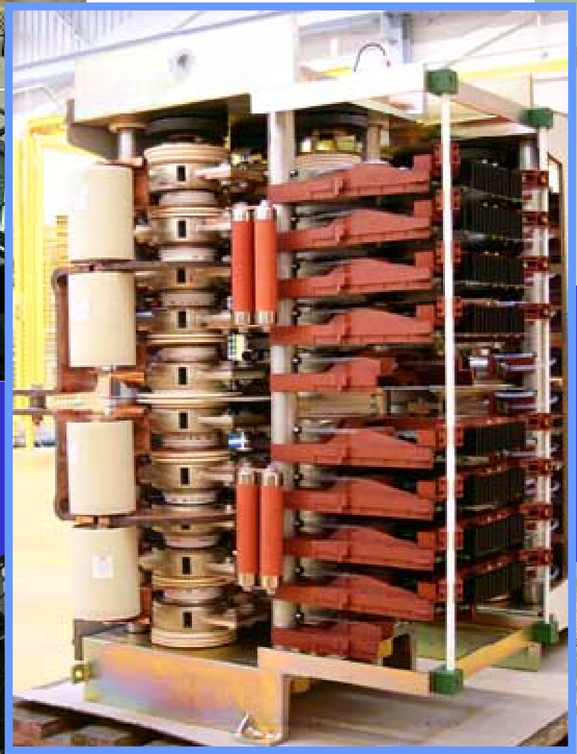
Power Electronic Building Blocks PEBB

MV IGCT PEBB based Power Conditioning Systems

Chip Manufacturing Plant,
DVRs (Dynamic Voltage Restorer)
installed: 2 units, 22 MVA each

Frequency Changers (FC)
DB Energie (Germany),11 units
installed to date, 18 MVA each

9MVA
IGCT PEBB



with a leading power density in MV applications

Regenerative Fuel Cell (RFC),
Power Quality for Columbus AFB
Mississippi Delivery 2002, 15MVA

BESS - Golden Valley Electric,
World's Largest Battery Energy
Storage System (BESS) installed at
GVEA, Fairbanks, Alaska,
40MW / 60MVA

Future Power Electronics Needs

Significant Reduction in:

- **Cost**
- **Losses**
- **Size**
- **Weight**

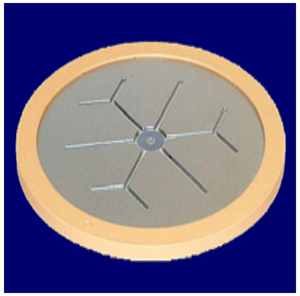
Significant Improvement in Switching Frequency

A Perfect Power Semiconductor Switch

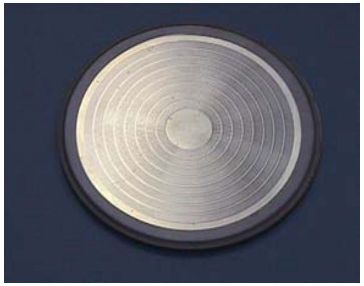
- Turn on and off instantaneously on command
- Zero switching losses
- Zero conduction losses
- Zero gate power requirements (accept digital signal for turn-on turn-off)

Need High-Voltage High-Power Building Blocks

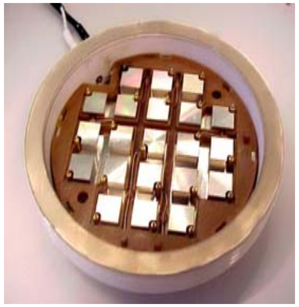
- **Packaged Building Blocks with Functional Specifications**
- **Programmable to serve multiple applications**
- **Can be connected in series and parallel to achieve higher ratings**



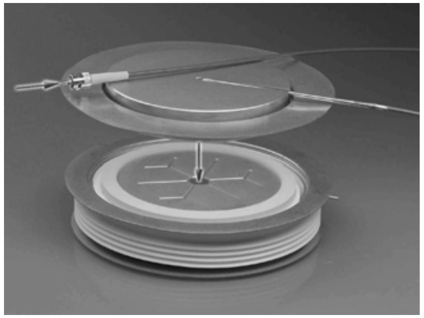
Conventional Thyristor



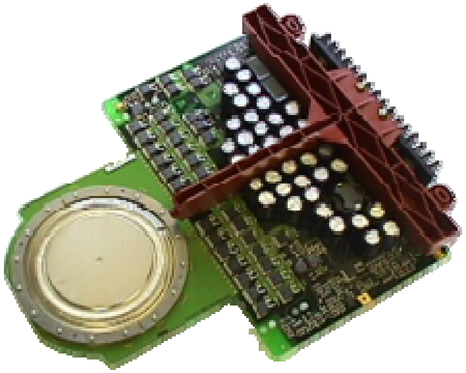
GTO



IGBT High Power Device



Direct Light Triggered Thyristor



Integrated Gate Commutated Thyristor

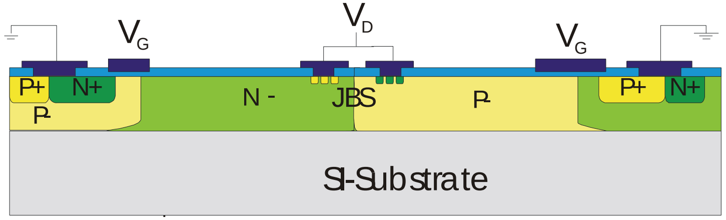
IGBT High Power Device

Press-Pack High Power Devices

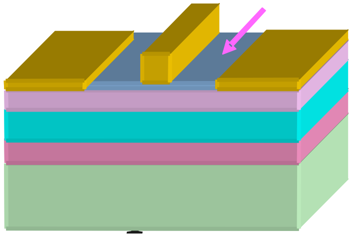
Advanced Power Devices

Reduce Losses and Raise Switching Frequency

- **Advanced Silicon Devices**



Low Losses; Fast Switching; Low Thermal Resistance; Bidirectional; Integration of Passives



SiC

- **Wide Band Gap Devices**

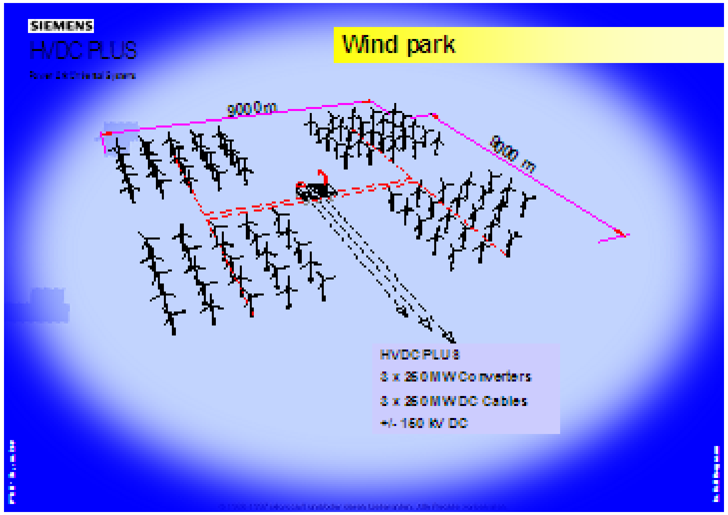
Silicon Carbide

HVDC Transmission for Integration of Wind Generation Farms in Transmission Grid

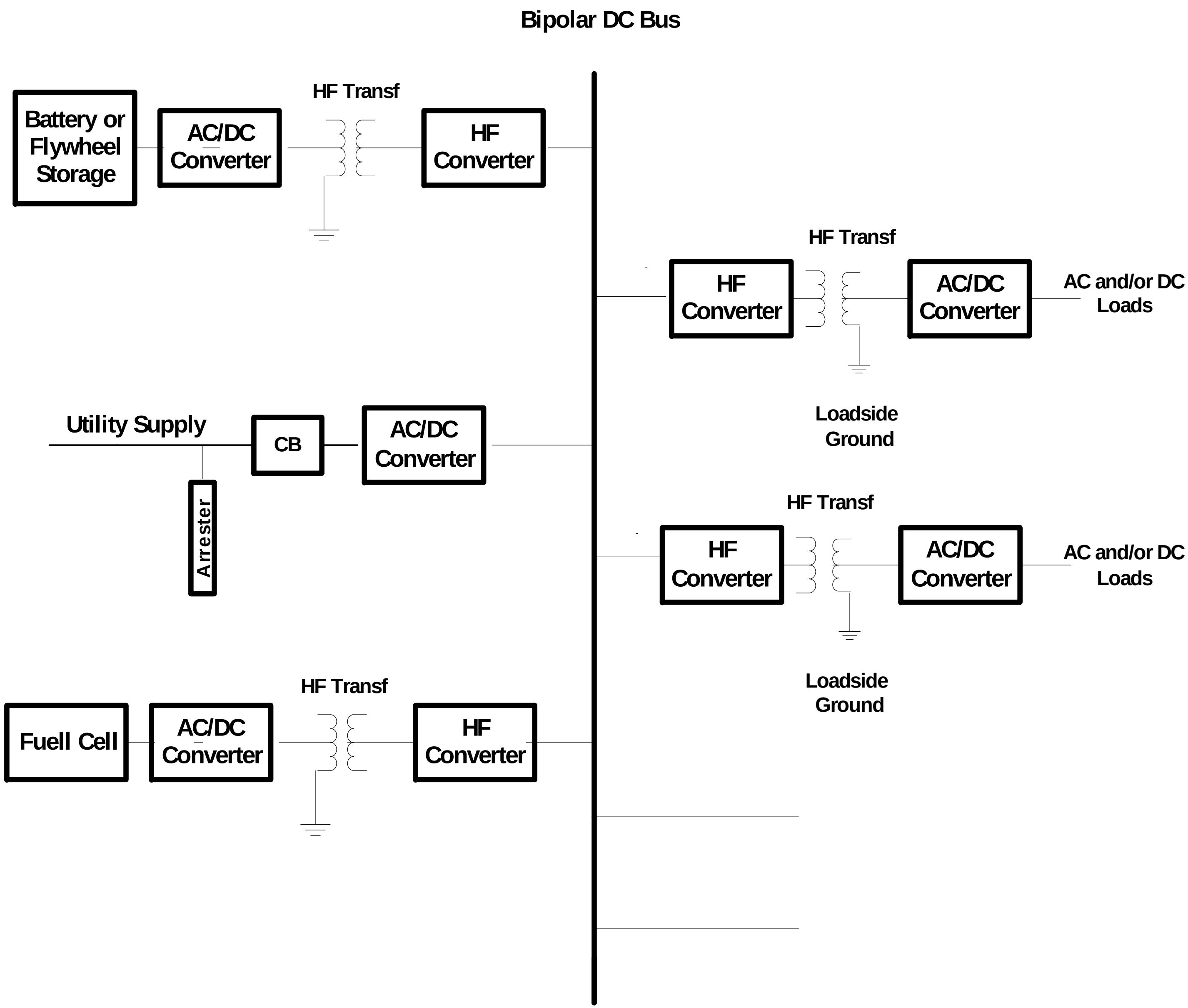
• **Obtaining Transmission ROW takes much longer than Building Wind Farms**

• **Underground DC Transmission with Voltage Sourced Converters could have**

- **Lower Cost**
- **Improved System Integration**
- **Much smaller Permit and Construction time**



Narain G. Hingorani



Proposed Conceptual Sub-transmission or Distribution System

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Session 2b

Reass I

POSSIBLE NEEDS AND APPLICATIONS OF POLYPHASE RESONANT CONVERTERS

by

W. A. Reass, D. M. Baca, and R. F. Gribble

Los Alamos National Laboratory

Jan 2007

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Abstract

High voltage polyphase resonant converters are a relatively new technology that can generate 100's of kV from a low voltage input source (few kV). The technology is fault tolerant and a shorted load will not harm the load or the converter. Fault energies are typically less than 10 joules. With multi-phase converters (>3) a lost or failed phase does not inhibit system operation. In addition, for very high power systems, converter modules can be added (e.g. 10 each 10 MW converters for 100 MW) as needed depending on the system load demands. This talk will review the research and applications to date that have been performed by Los Alamos National Laboratory.

Outline

- Review of Polyphase Resonant Power Conditioning Technology
- Design Possibilities of Large “MW” Class Converter-Modulators
- Smaller, Higher Frequency MOSFET Converter-Modulators
- Conclusion

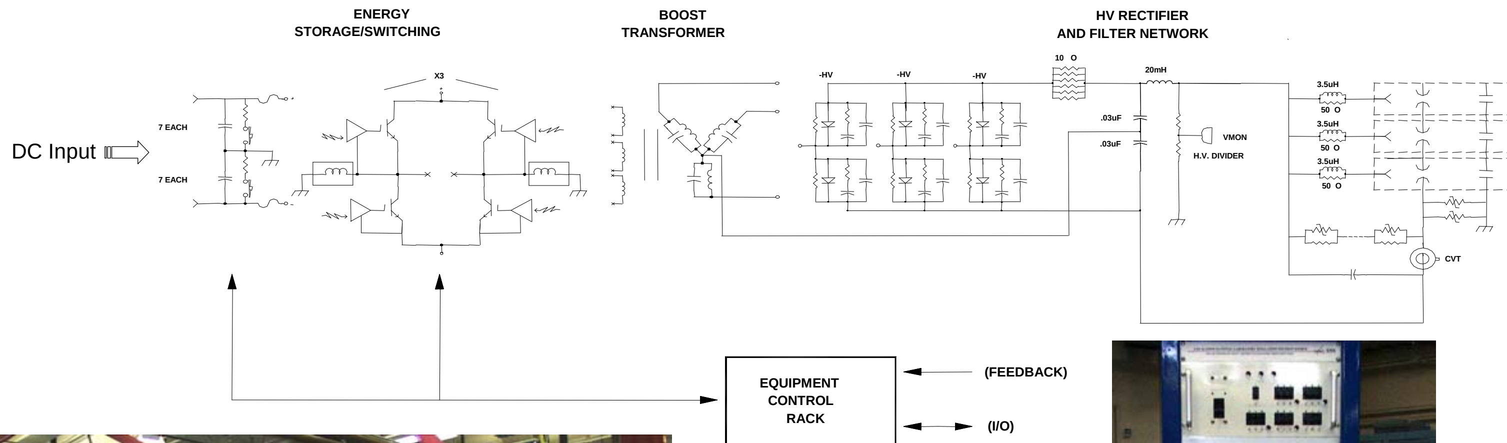
What is Polyphase Resonant Power Conditioning?

- New method to generate high voltages from low with very high power
- Essentially a large (polyphase and resonant) DC-DC Converter
  - At least 1/10 size, weight, and volume of any previous method
- Uses recently proven technologies
  - Traction Motor Metallized Hazy Polypropylene Self-Clearing Capacitors for energy storage
  - Multi-megawatt capable Insulated Gate Bipolar Transistors
- Transformer cores of Amorphous Nanocrystalline Alloy
  - 1,000 times more efficient than steel
  - 1/300 core <u>volume and weight</u> for same power as 60Hz steel
- Polyphase resonant voltage multiplication to further minimize transformer volume and weight
- Easily scaleable to 10’s of MW and 100’s of kV
  - Easily optimized for various use (and lower power/voltage)
- Design is fault tolerant and inherently self-protective
  - Protect systems not necessary
  - Permits long cable lengths and remote location

Polyphase Resonant Power Conditioning Uses LANL/LANL Funded Technology Developments

- Low Inductance Self-Healing Capacitors
  - Thomson Passive Components (AVX), France
- Low Inductance High Power Capacitors
  - General Atomics Energy Products, San Diego, Ca.
- Amorphous Nanocrystalline Core Material
  - MK Magnetics (Stangenes), Adelanto, Ca.
- New Engineering Techniques
  - Polyphase Resonant Voltage Multiplication
  - Resonant Rectification
  - Self DeQing (No crowbars and self protective)
  - Snubberless IGBT Switching

Simplified Block Diagram of Polyphase Resonant Converter Modulator (10 MW Long Pulse)



HIGH VOLTAGE CONVERTER MODULATOR

EQUIPMENT CONTROL RACK

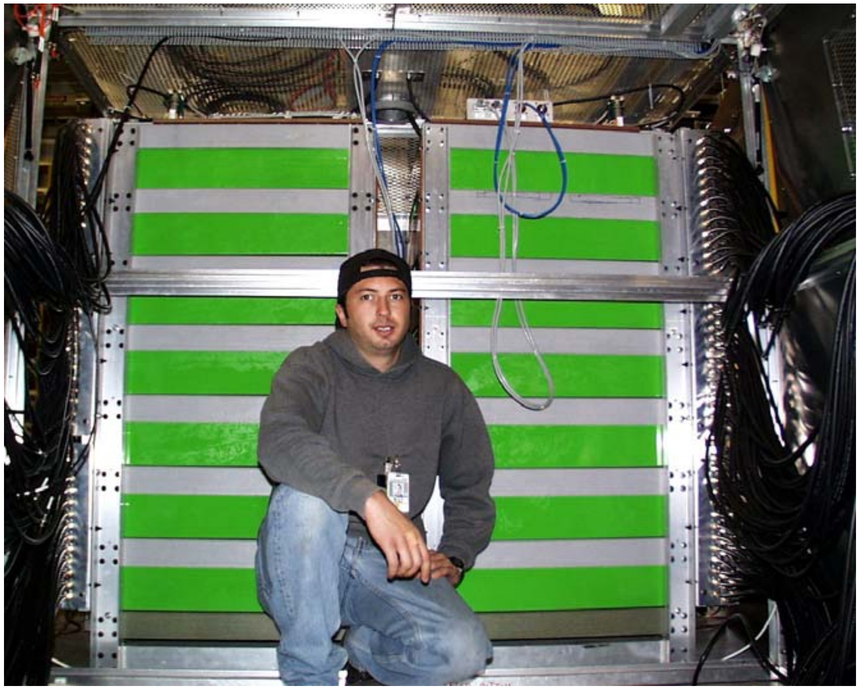
Los Alamos High Frequency "Polyphase Resonant Power Conditioning" Compared To Conventional 60Hz Technology Is Significantly Smaller

10 Megawatt Pulse, 20 KHz, 140 kV
Polyphase Resonant Converter-Modulator

- Developed for Oak Ridge SNS Accelerator
- All components operate at 10 MW level
- Can be optimized for 10 MW CW
- Can be optimized for 30 MW Long Pulse
- Resonant conversion is fault tolerant
- Small and compact
- Reliable components
- Can operate with kilometer cable lengths
- No protection networks needed

Los Alamos Low Voltage Energy Storage Compared To Conventional High Voltage Method Is Very Compact And Reliable

Self-Healing Metallized Hazy Polypropylene



- 300,000 hour lifetime
- Graceful degradation
- High frequency design, variable rep-rate capabilities
- Extremely high volumetric efficiency
- High safety factor

Conventional
High Voltage Paper and Foil Capacitors

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

Nanocrystalline High Frequency Transformers Are Over 150 Times Lighter And Significantly Smaller

Typical H.V. Transformer

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

HVCM Transformer

- 140 kV, 20 KHz
- 20 Amp RMS
- 1 MW Average (3) present use
- 450 LBS for 3
- 3 KW Loss At 2 MW

Load Protection Networks Not Needed For Los Alamos Technology

Typical H.V. Crowbar Protect Network

- Large
- Reliability concerns
- Maintenance concerns

Resonant Converter Protect Network

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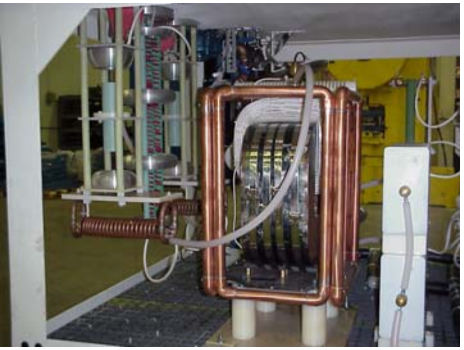
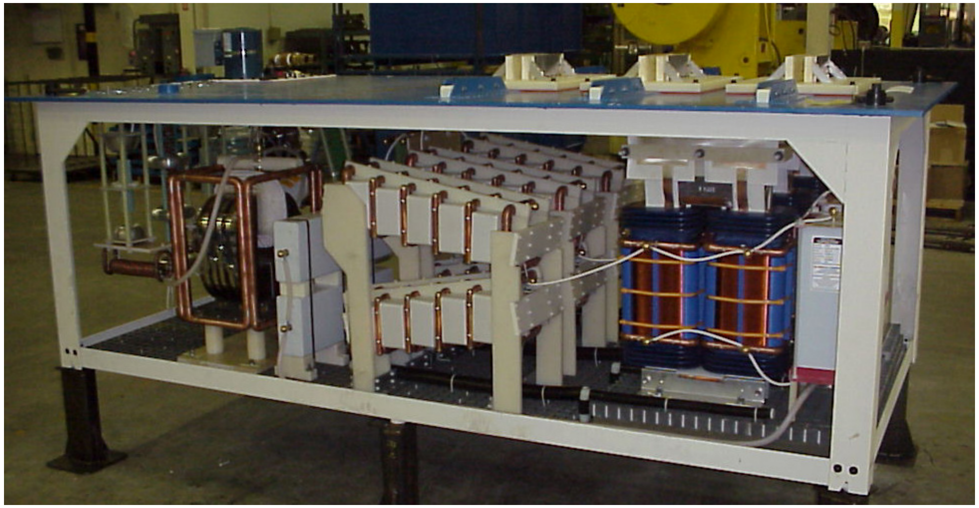
(none required)

- Converter-Modulator inherently self protective
- Automatic fault "ride-through"
- Safe for all components

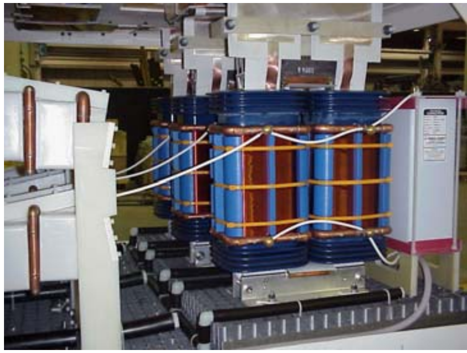
Tank Basket Assembly; 1 MW Average, 10 MW Long Pulse



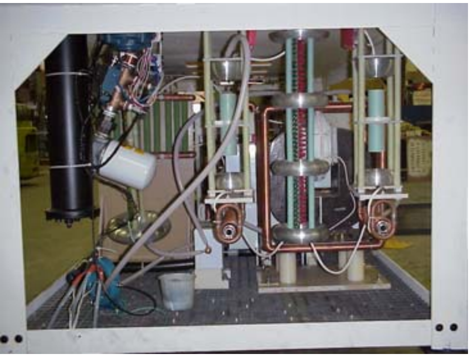
Filter Network



Tank Basket Assembly

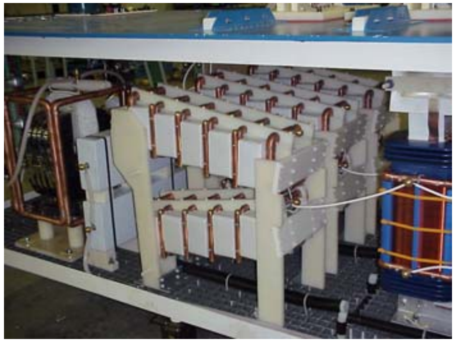


Transformers

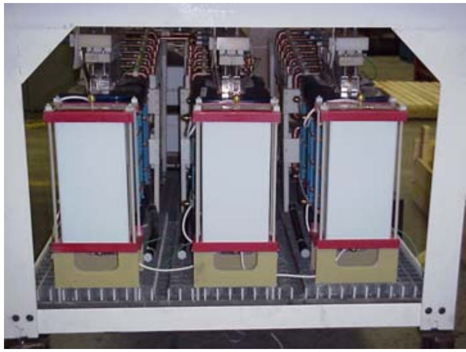


Output Sockets
&
Varistor Assembly

Oil Pump & Voltage Divider

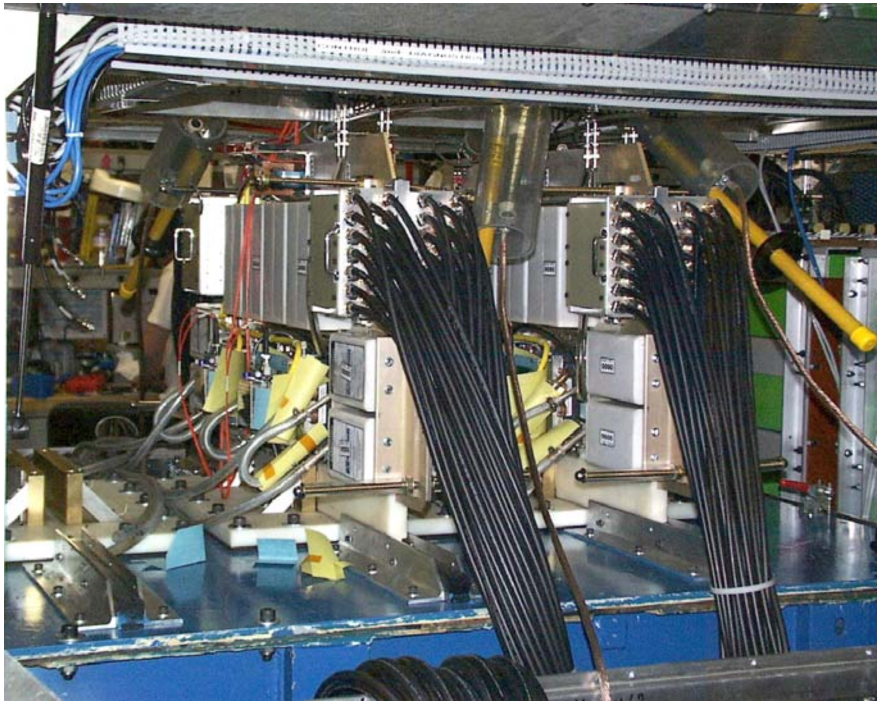


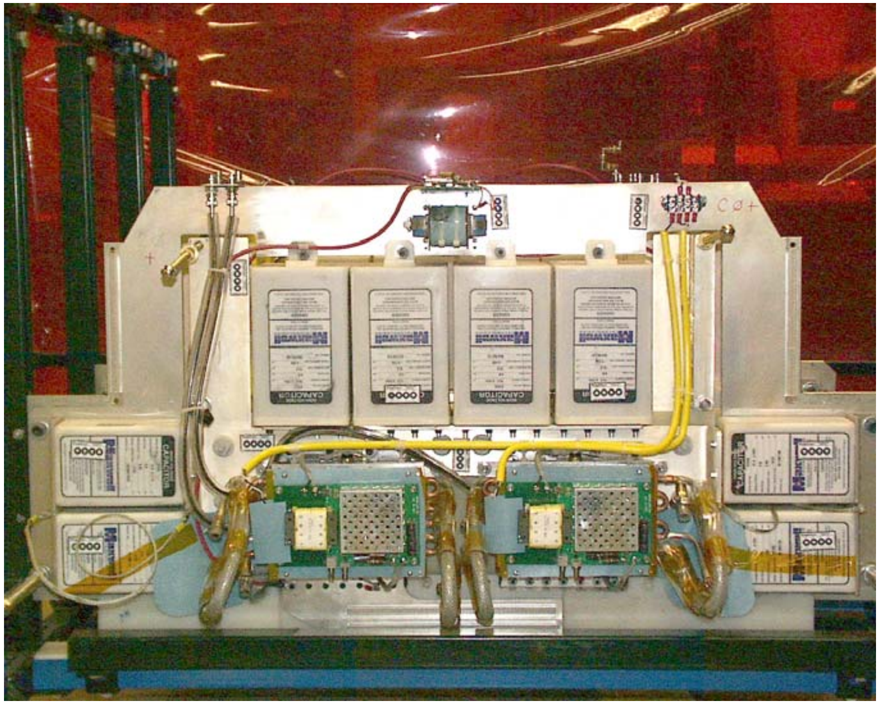
Diode Rectifiers



Transformer Resonating Capacitors

IGBT Switch Plate Assembly; 1 MW Average, 10 MW Long Pulse

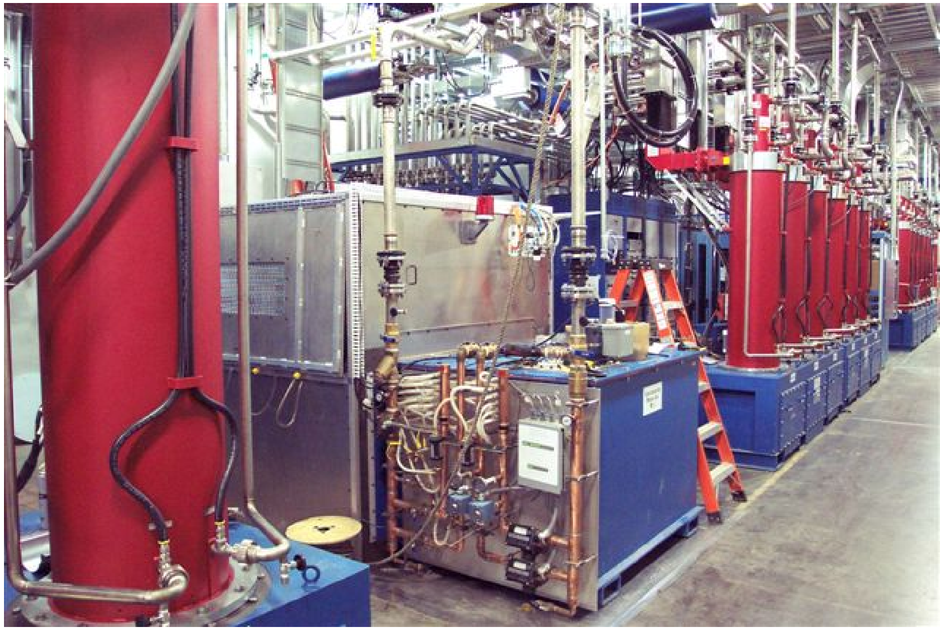




- Already operates at 10 MW switching level

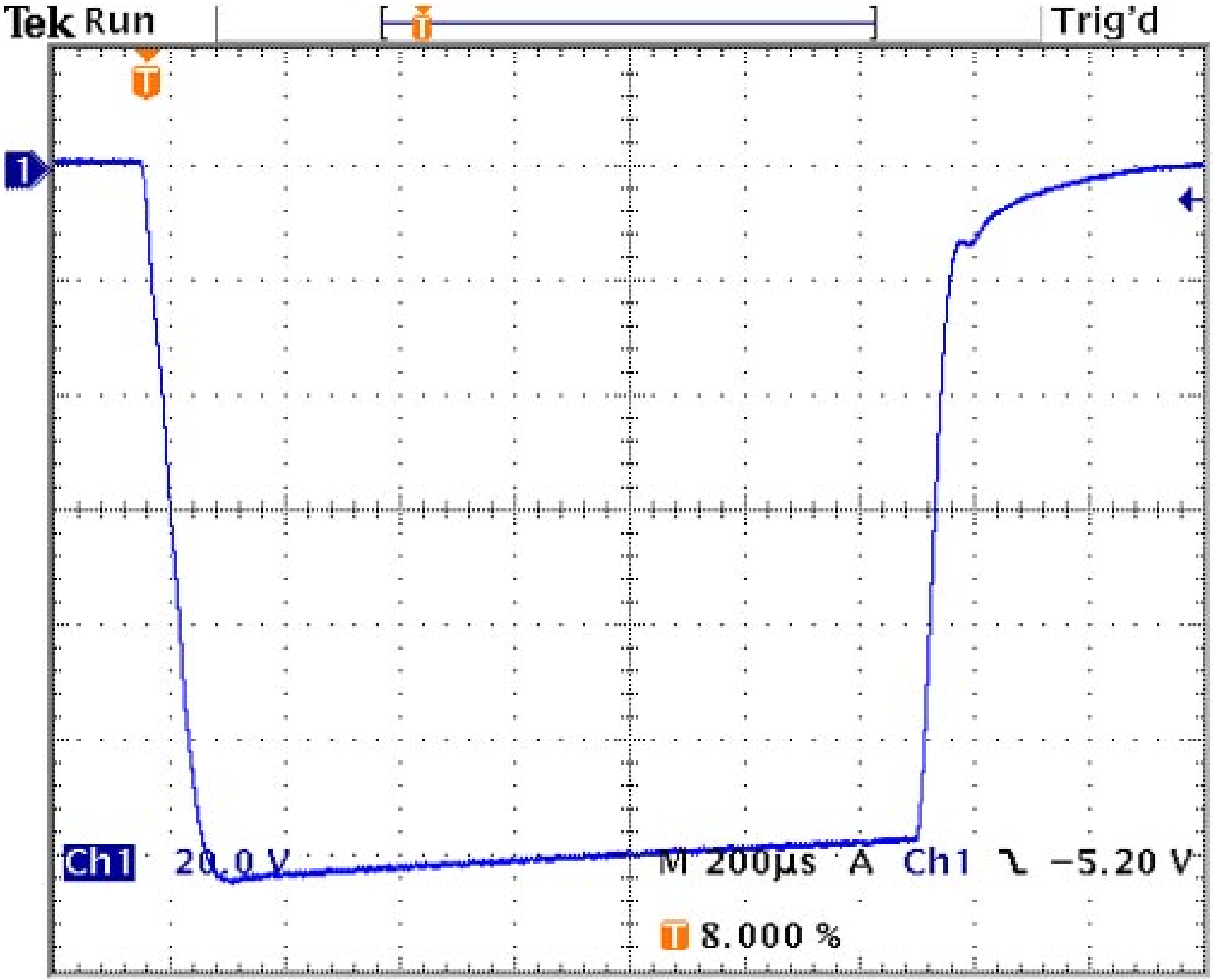
Views of Installed Converters at Oak Ridge

<u>DTL-ME3 with Klystrons</u>
"The Workhorse"

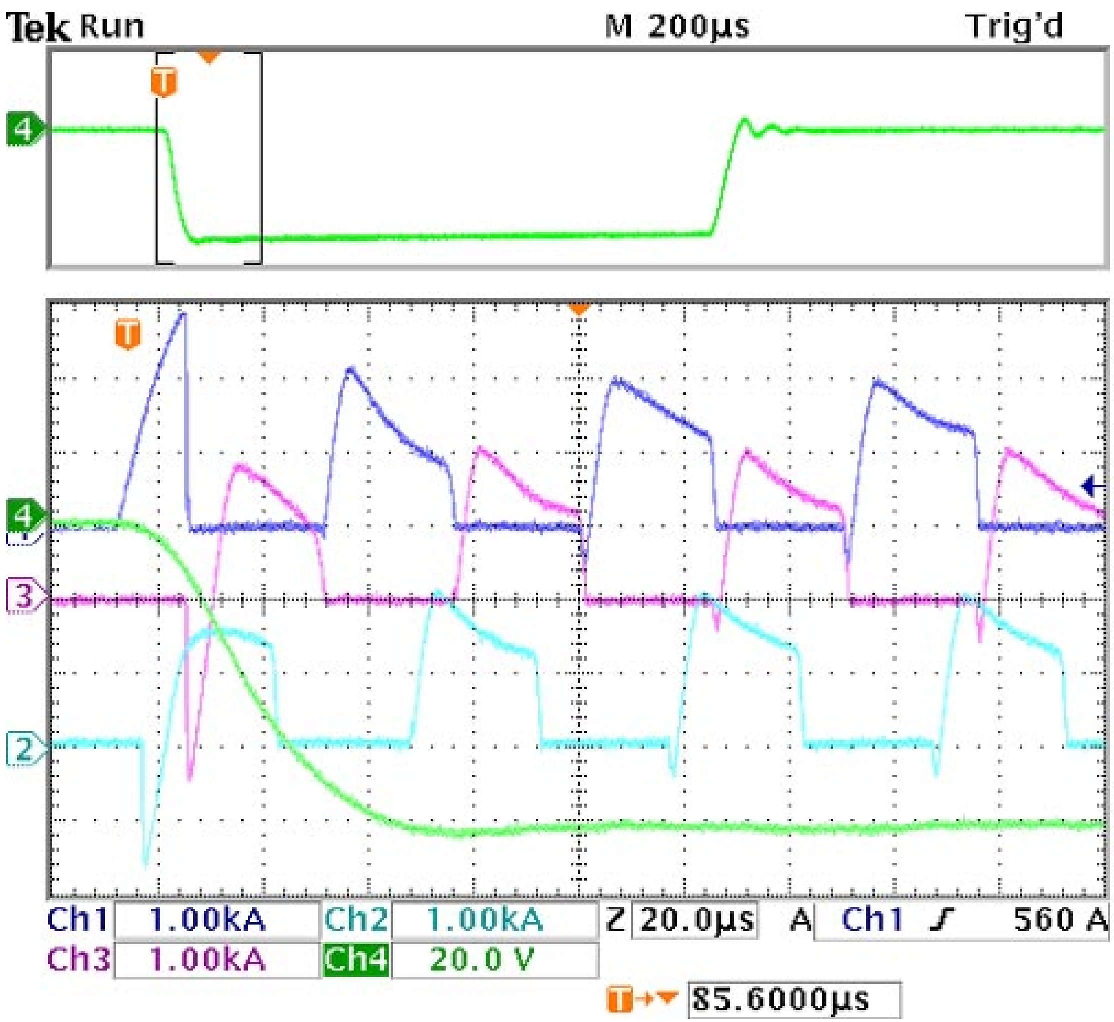


<u>SCL-ME1 with 12 pack</u>

125 kV, 10 MW Pulse for 402 MHz Klystrons



12 Klystron, 75 kV Operation (9.25 MW)



Output Voltage
(~75 kV)

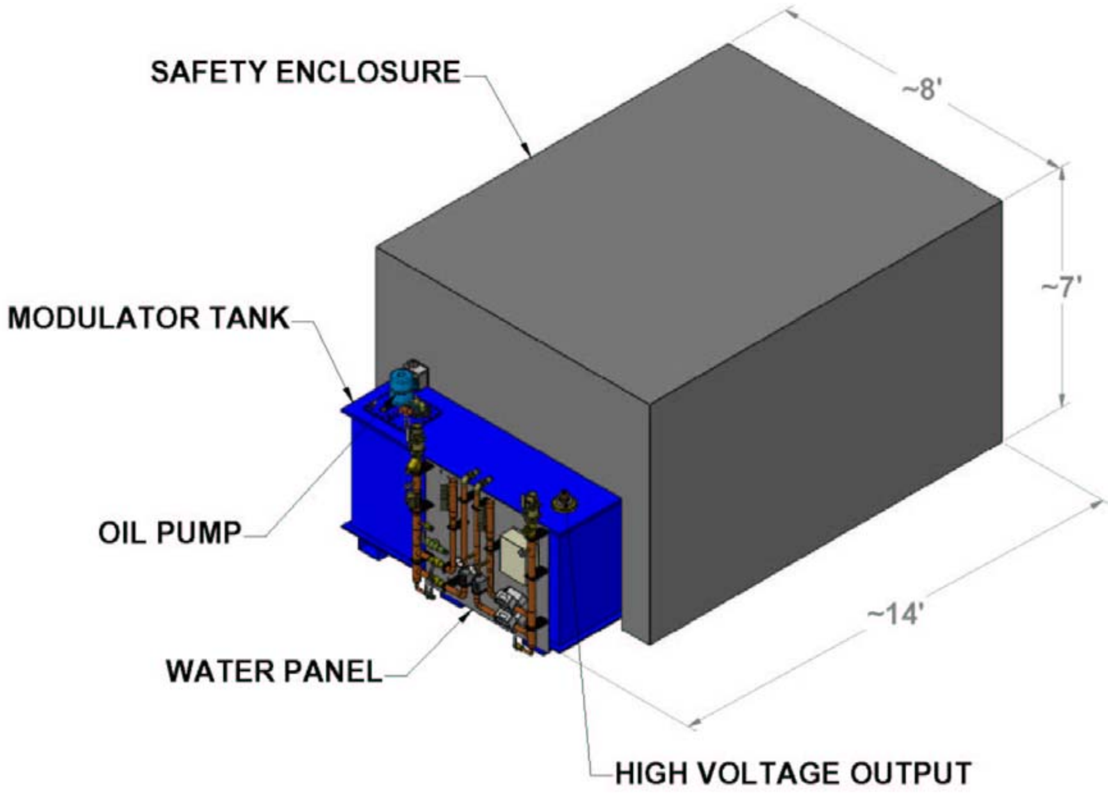
IGBT Switch Current
(1 kA/Div)

Capabilities of Polyphase Resonant Conditioning

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

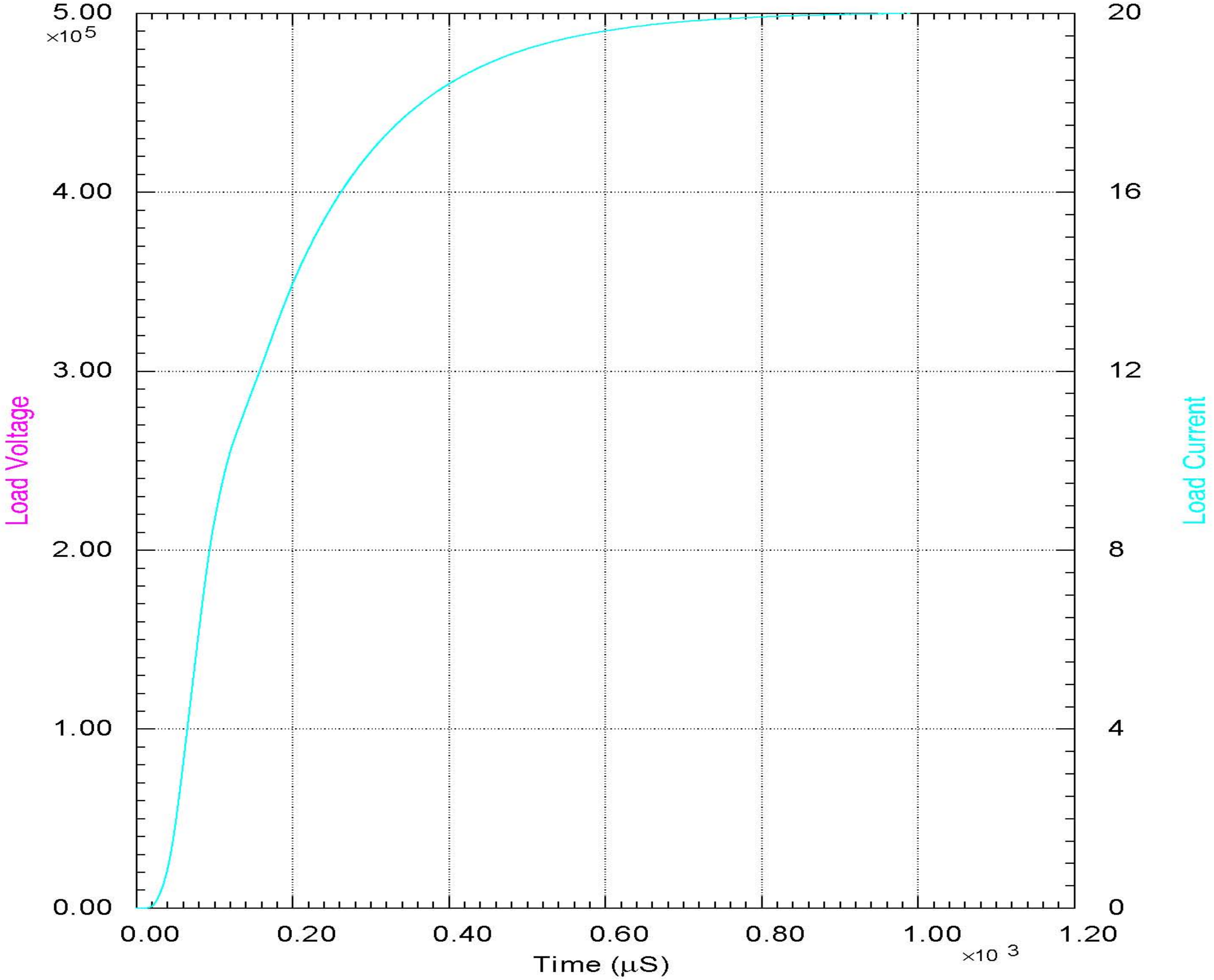
View Of a Proposed 30 MW Pentaphase Converter-Modulator System (Pulsed)

Size: 7’ X 8’ X 14’

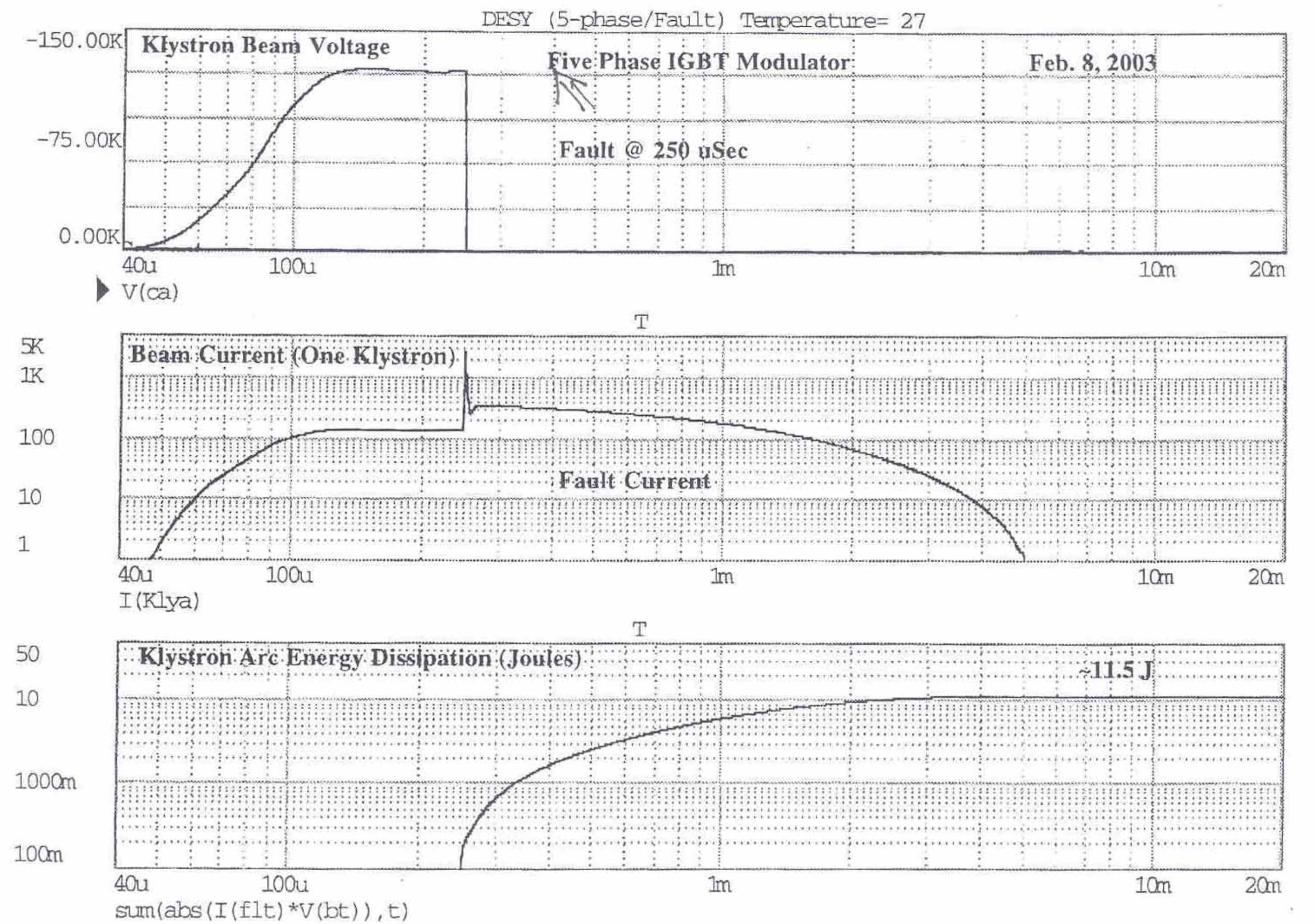


- Fault tolerant, automatic fault “ride-through”
- Can operate with long output cables (over 1 kilometer)
- Cannot harm load or self
- Multiple units operate from common DC bus
- Different Optimization for CW
- Present Designs Limited by Switching Devices

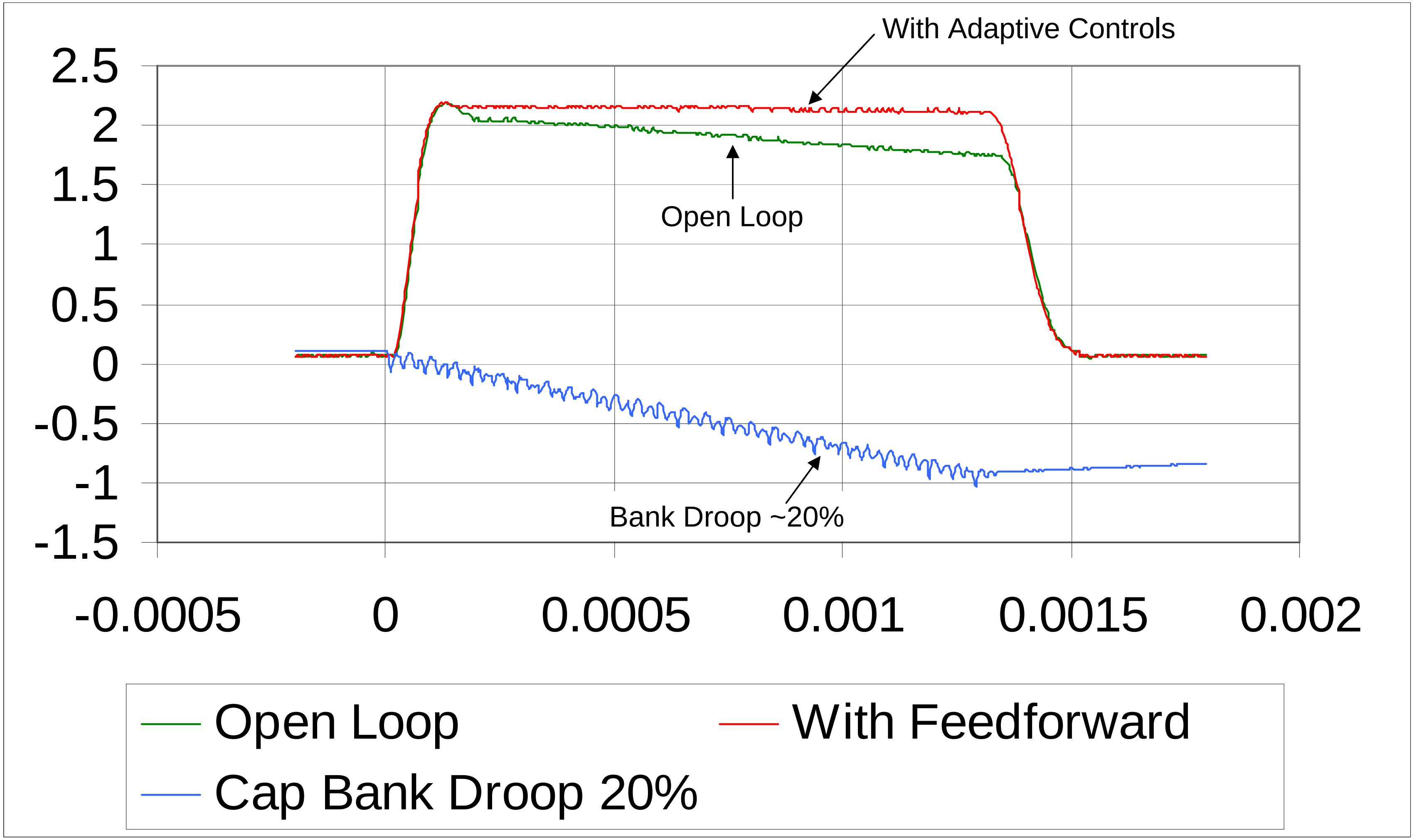
500 kV Converter Rise Time Detail



Klystron Fault Energy – 1KM Of Cable (125 kV)

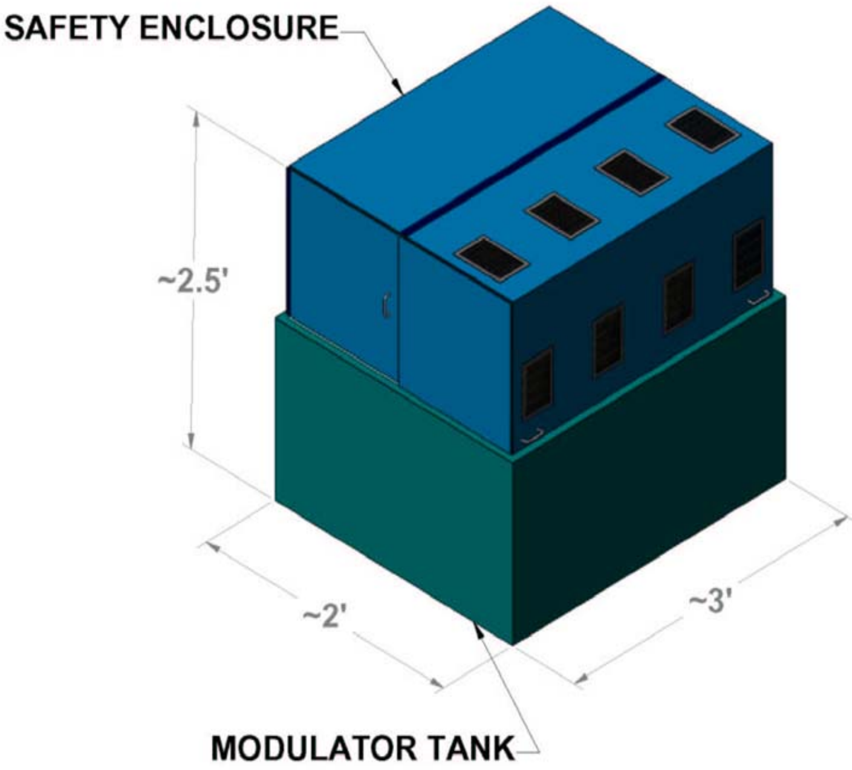


Novel Adaptive Feedforward/Feedback For Converter Control



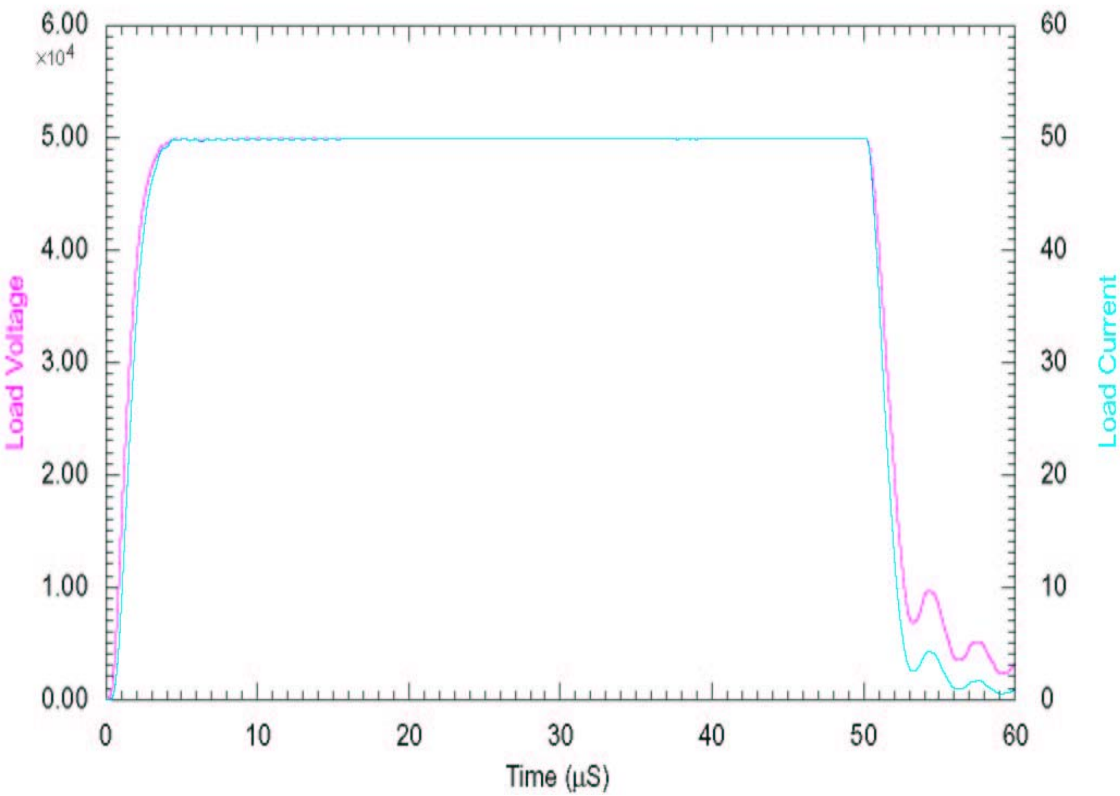
View of 2.5 MW Pulse, 250 KW Average, MOSFET Converter-Modulator

Size: 2.5’ X 2’ X 3’



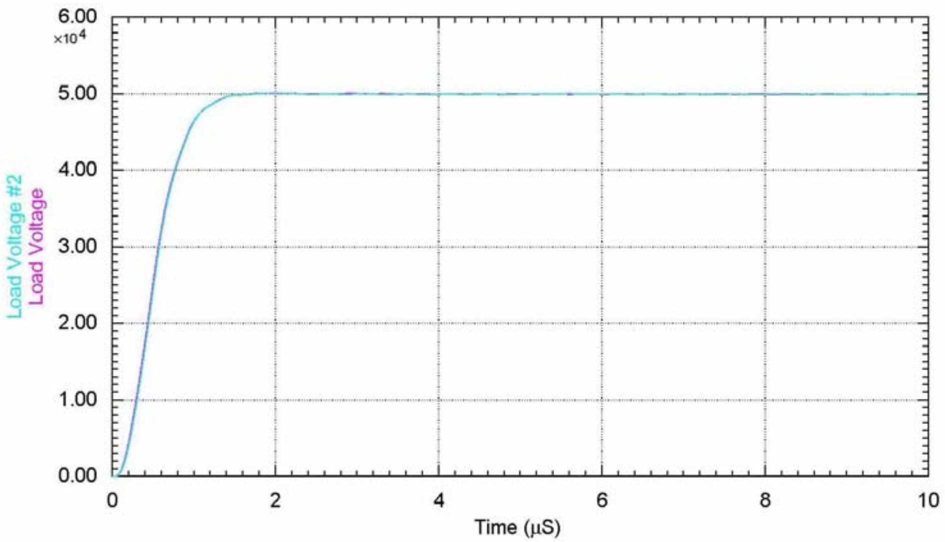
- Design Based On Available Components And MOSFET Switches
- Higher Frequency And Smaller
- Can Be Optimized For Mobile/Airborne Applications
- Typical Uses May Be Search Radar, DE, And Medical Applications
- Pulse Width/Rep-rate/Voltage Agile
- “CW” Designs Also Possible

Model Output Of Medium Pulse Converter

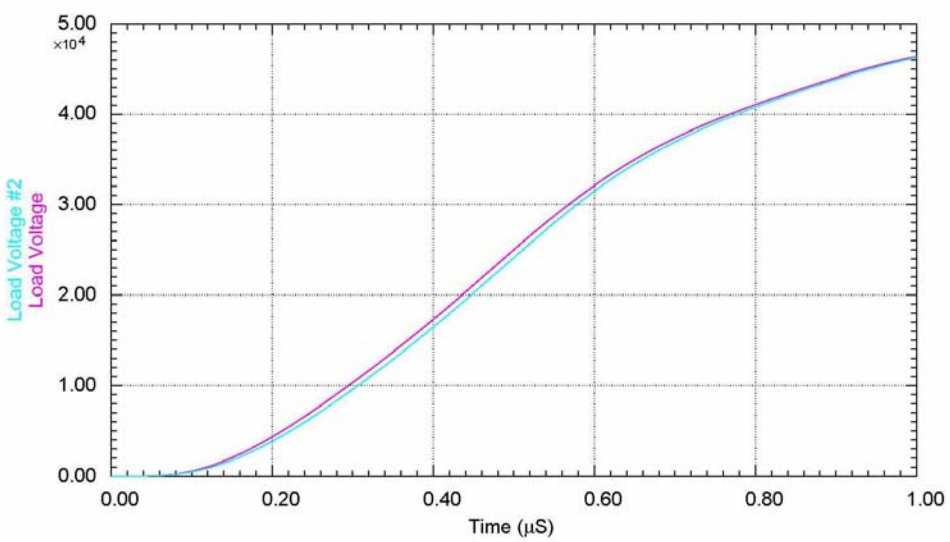


- Rectified 480V 3Ø Input
- 50 kV Output
- 50 Amp Output
- Tr, Tf ~ 800nS
- ~ 94% Efficiency
- Other Optimizations Possible
- Pulse Width And Voltage Agile
- Multi KHz Rep-Rate

Soft Failure Mechanism 12 Pulse / 10 Pulse



10 & 12 Pulse Output Voltages "Overlay"
(2 failed switching assemblies)



Slight Change In Rise Time For
10 Pulse vs. 12 Pulse Operation
(no significant difference)

Possible Applications Of Fault Tolerant Polyphase Resonant Converters

- Motor Drives
  - At Remote Locations
- Radar Modulators
- Power Distribution Networks
- Directed Energy, Area Denial Systems
- High Power Transducers/Drivers
- Electronic Pulse Generators
- Power Converters/Chargers For Pulse Power Application

Conclusion

- Los Alamos Developed Polyphase Resonant Power Conditioning Design Topology Techniques Now Proven
- Semiconductors Limiting Elements in Present Designs
- Designs Can Be Optimized For Any Load Or Pulse Requirement
- Efficient Adaptive Feedback Control Methods Now Possible
- Inherently Self And Load Protective
- Significant Change In High Power, Power Conditioning Topology
- Ideal For Many Military, Medical, Broadcast, And Scientific Applications
- Systems Installed At LANL, ORNL, And SLAC

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Session 2b

Staines I

High-Megawatt Converter Technology Workshop

High-Voltage, High-Megawatt Power Requirements at GA

Dr Geoff Staines

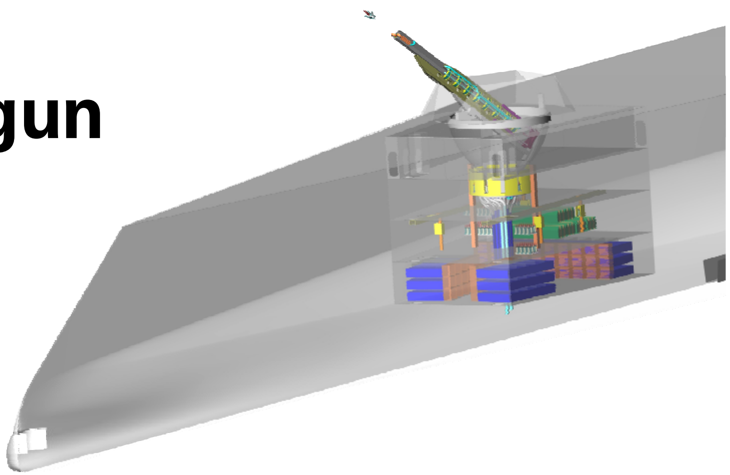
General Atomics – Electronic Systems Inc

24 Jan, 2007

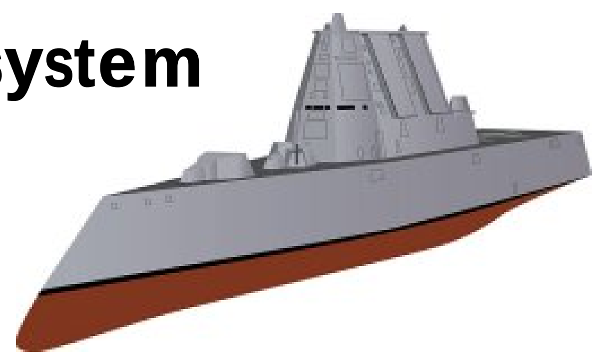
Selected GA Power Conversion Projects

- Electromagnetic Aircraft Launch System (EMALS)

- Rail gun

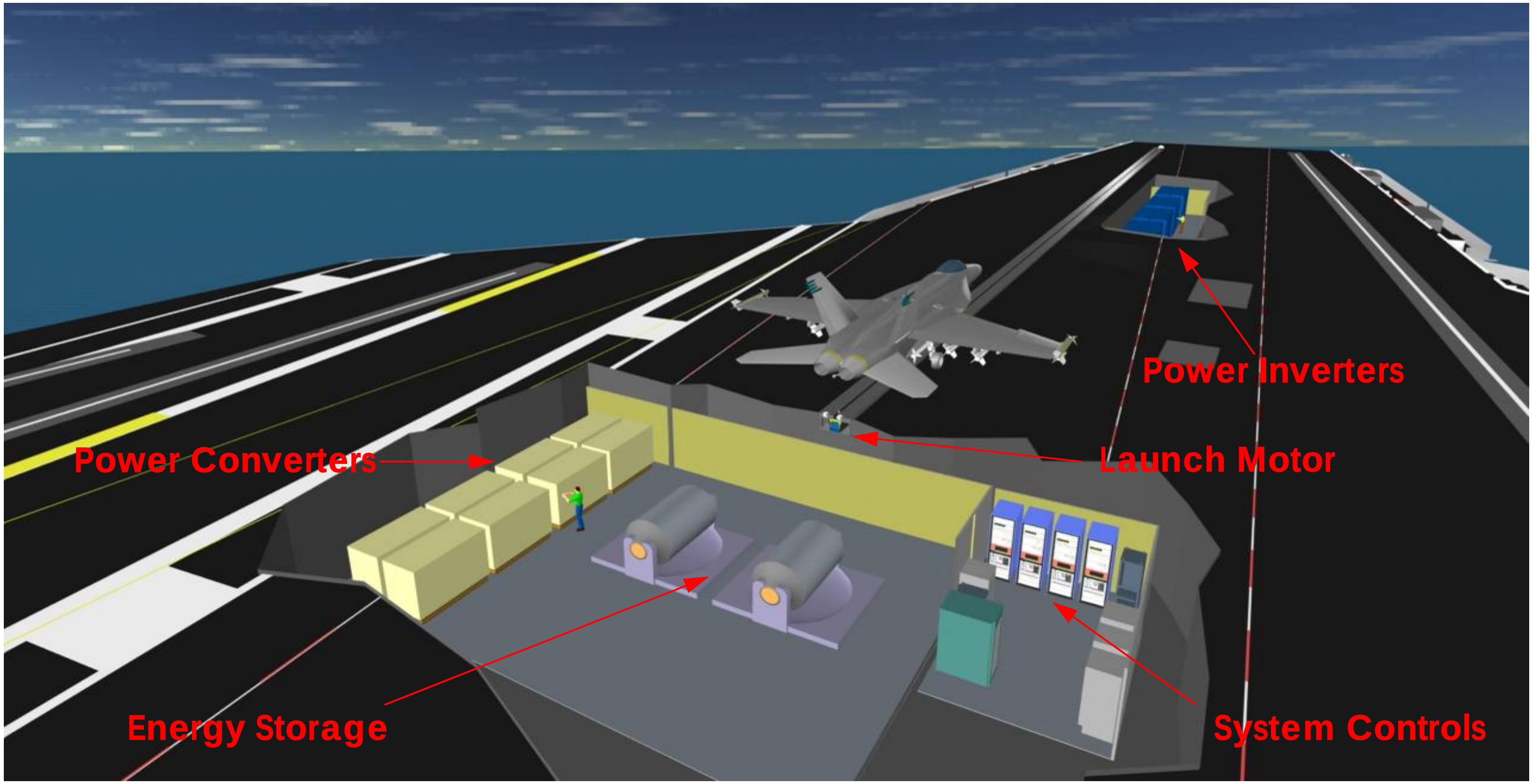


- Electric ship integrated power system



EMALS Concept

- IGBT-based inverters
- 150 MW over 2-3 seconds



EMALS Inverter Issues

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

Future EMALS Switch Characteristics

PARAMETER	Where We Are	Where We Want to Be
Voltage	3300 V	5000 – 6000 V
Current	1500 A	2000 – 3000 A
Repetitive Peak Current	2400 A	4800 A
Forward Voltage Drop	2.5 V	2.0 V
Turn On Time	0.2 μs	0.02 μs
Turn Off Time	0.8 μs	0.08 μs
Switching Frequency	15-20 kHz	20 kHz
Thermal Resistance (junc-case)	0.0085 K/W	0.0042 K/W
Thermal Resistance (case-sink)	0.004 K/W	0.002 K/W

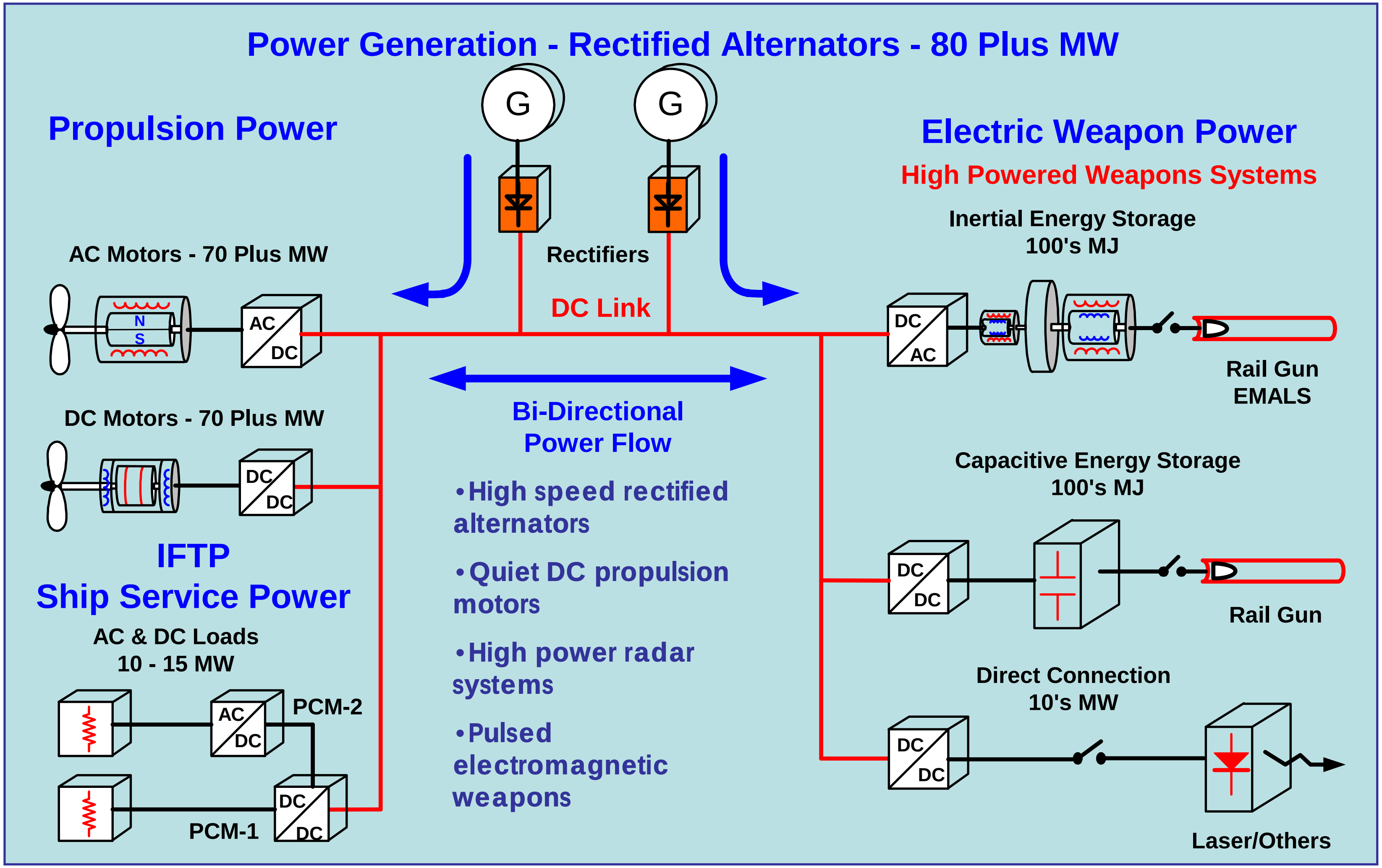
Integrated Power System (IPS) Electric Propulsion and Ship Service Power

- The first surface combatant using IPS is DDG 1000 with two propulsion motors rated at 37 MW and ship service loads > 12 MW

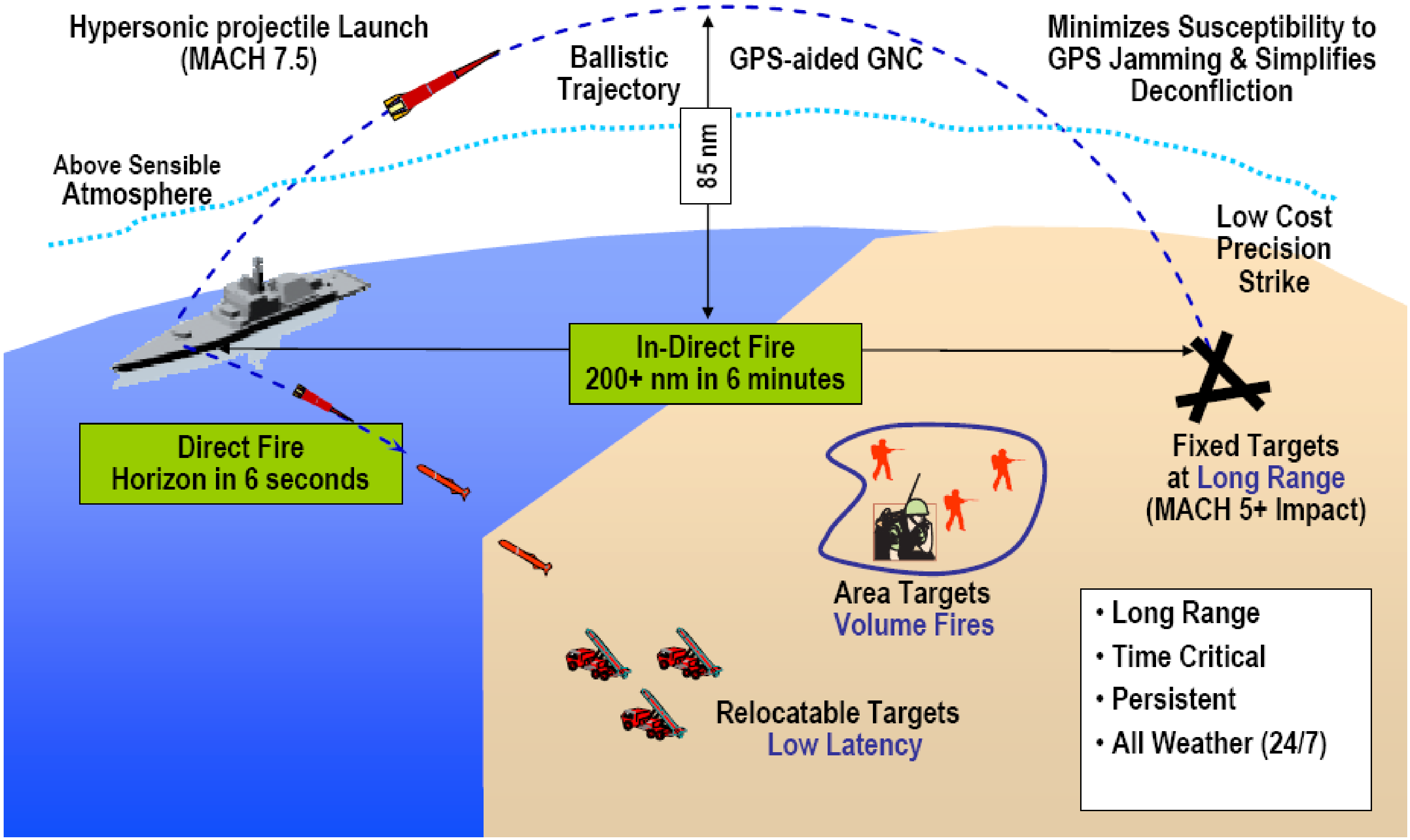
DDG 1000

- This is a major first step for IPS, but what are the next steps to meet the future IPS needs?
- Spiral insertion of new mission systems such as pulse energy weapons will increase the electric load demands even further

Flexible Power Generation, Distribution and Management

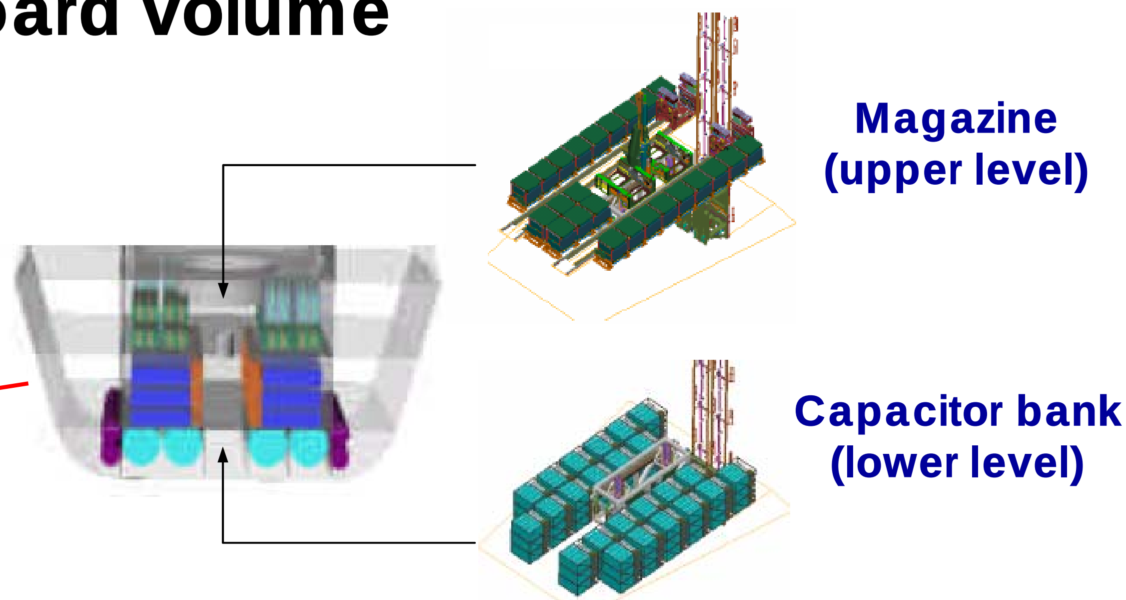


Rail Gun Mission



Rail Gun Power Requirements

- **Current source to charge 200 MJ caps to 11 kV**
- **Max 10 shots per minute → 35 MJ/s average**
- **Prime power from two 35 MW MT-30 turbines**
- **Require high power density (> 2 MW/m^3) to fit in available shipboard volume**



Charging of msec-Pulse EM Weapon Systems

- **Repetitive operation requires MW-class charger**
- **Largest part of rail gun system is cap bank**
- **2 J/cc available for charging times < 20 sec**
- **Fast charging minimizes capacitor volume, *even for single-shot operation***
- **Energy density of established capacitor films is saturated – look for reductions in rest of system**
- **Charging supply is next largest sub-system**
- **High power density MW-class chargers fundamental to practical pulsed EM weapons**

Session 3

Hefner I

High Megawatt Fuel Cell Power Converter Technology Impacts Study

(NIST/DOE Interagency Agreement)

Allen Hefner

NIST

Outline

I. Introduction

II. Analysis of new technology impacts

III. PCS approaches being considered

   A. Low Voltage Inverters

   B. Medium Voltage Inverters

   C. High Power Architectures

IV. Inputs from High-MW community

I. Introduction

Objective: Perform Independent Analysis (non commercial bias) of technologies that may reduce cost of Power Conditioning System (PCS) for future Fuel Cell Power Plants

Motivation:

- DoE SECA cost goals:
  - FC generator plant $400/kw
  - including $40-100/kW for power converter
- Today's FCE cost:
  - FC generator plant $3,000/kW
  - including $260/kW for power converter (to 18 kVAC)

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II. Analysis of Technology Impacts

- Methodology for impact study:
  - Classify power converter architectures and component technologies that may reduce cost
  - Perform tabular calculations of cost for each option using estimated advantages of new technologies
  - Use component modeling, and circuit and system simulations to verify and refine calculations
- Consider power electronics and/or transformer up to 18kVAC, and assume transformer from 18 kVAC to transmission level voltage

Analysis of Technology Impacts (cont.)

- Boundary conditions and performance parameters:
  - FC Stack: center tap ~700 VDC, 1000 A
  - Individual FC stack current control (may be necessary for FC reliability)
  - Fault tolerant and serviceable

- Converter cost components:
  - Semiconductors
  - Module Packaging
  - Cooling System
  - Magnetics: Filter Inductors and
HF voltage isolation transformers
  - Transformer up to 18kV
  - Breakers

Outline

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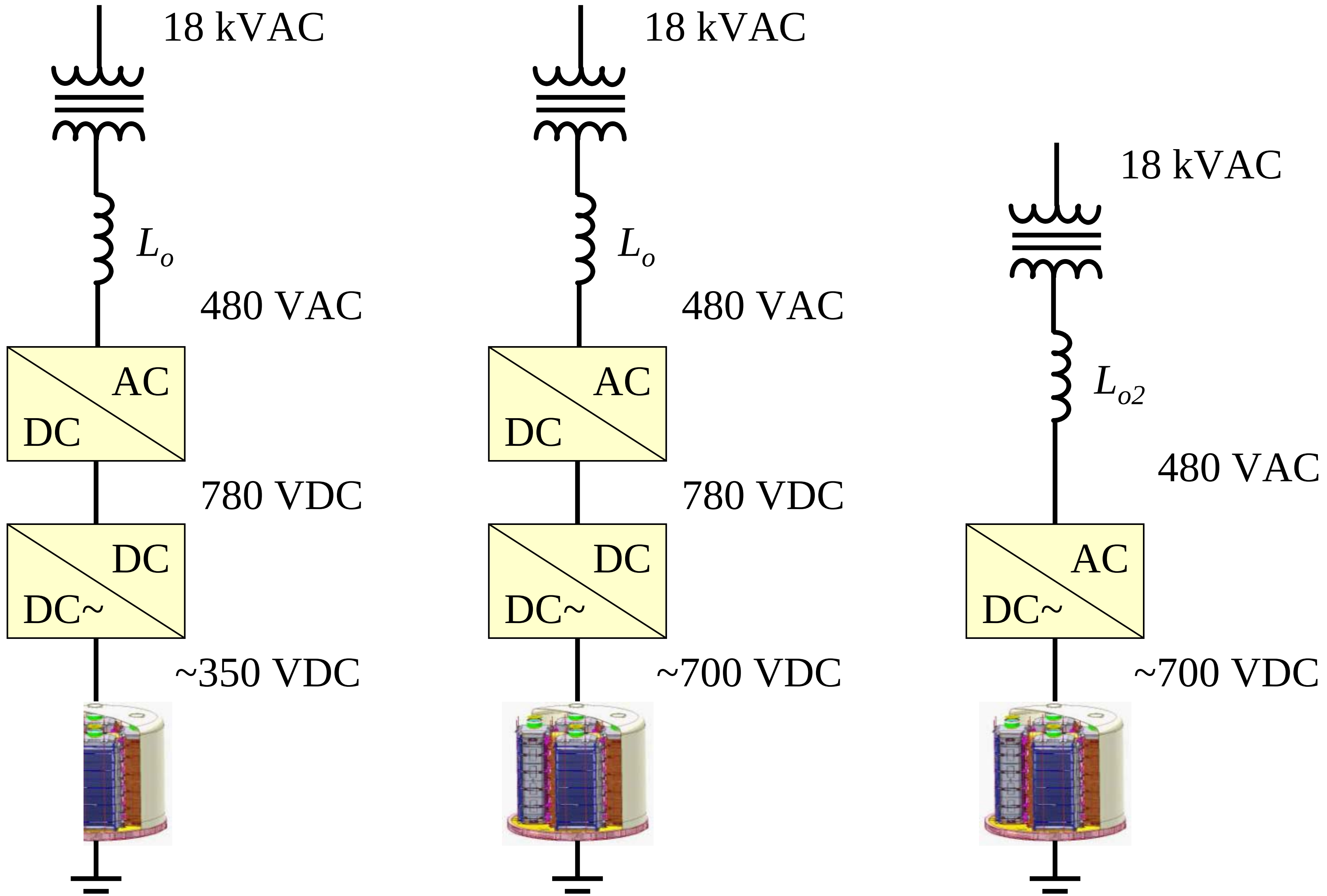
IIIA. Low-Voltage Inverters

(Inverter to 480 VAC, then transformer to 18 kVAC)

1) ***First Generation:*** ~350 VDC FC, two stage DCDC/inverter:
750 VDC, 480 VAC

2) ***Baseline:*** Center-tap ~700 VDC FC, two stage regulator/inverter:
750VDC, 480 VAC
   – 1200 V is "Sweet spot" is silicon semiconductors

3) ***Present Generation:*** ~700 VDC FC, single stage inverter:
480 VAC
   – Fewer semiconductors because single stage
   – Larger filter inductor due to unregulated DC (filter sized for max VDC)
   – LV-DC Common Bus would stress FCs



1) First Generation ***2) Baseline*** ***3) Present Generation***

Low-Voltage Semiconductors

- **Baseline:** 1200 V silicon IGBT switch and silicon PiN diode
  - 1200 V is sweet spot for silicon IGBTs at 15 – 20 kHz switching
- 1200 V silicon IGBT switch and SiC Schottky diode
  - More efficient at 20 kHz → less heat removal cost
    → lower temperature and longer life
  - Less EMI → less filter inductor cost
  - *What is cost break point or 1200 V SiC Schottky?*
- 1200 V SiC MOSFET Switch and SiC Schottky diode
  - Higher Frequency for DCDC but not necessary for inverter
  - *What is cost break point for 1200 V SiC MOSFET Switch?*

IIIB. Medium-Voltage Inverters

(Inverter to 4160 VAC, then transformer to 18 kVAC)

- Low voltage inverters require:
  - high current (1000 A) for 0.6 MW FC
  - high part count for 300 MW Power Plant (500 Inverters!!!)

- Medium Voltage Inverter: DCDC converter(s) to 6 kVDC, 4160 VAC inverter, transformer to 18 kVAC
  - Lower current semiconductor for inverter (140 A) for 0.6 MW FC
  - Multiple FCs for one high power inverter

High-Voltage Semiconductors

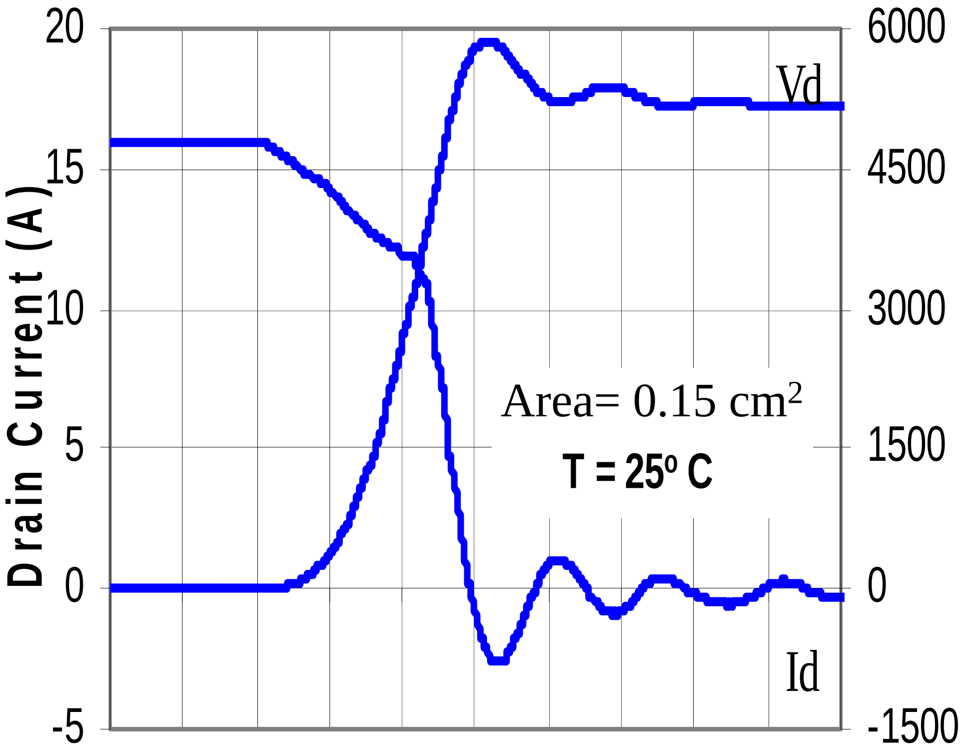
- **Baseline:** High Voltage Silicon Semiconductors (IGBT, IGCT)
  - Typically ~6 kV blocking voltage maximum
  - Require multi-level inverter for 4160 VAC (more semiconductors)
  - Low switching frequency (2 kHz) requires larger filter

- High-Voltage, High Frequency SiC Switch and Diodes
  - 10 kV, 20 kHz MOSFET switch and Schottky diode
  - Less filter inductor requirements due to high frequency
  - Fewer Semiconductors due to fewer levels
  - *What is cost break point for HV-SiC Power Semicoductors?*

DARPA HPE MOSFET

High Speed at High Voltage

SiC MOSFET: 10 kV, 30 ns **Silicon IGBT: 4.5 kV, 2us**



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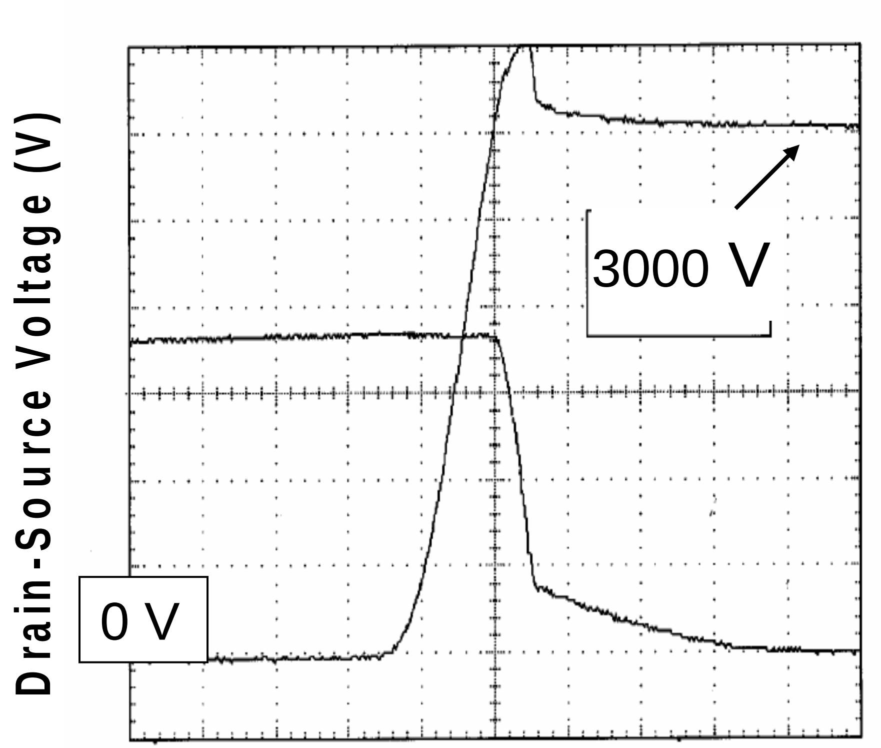

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IIIC. High Power Architectures

(8 X ~700 VDC FC to 4160 VAC)

1) Individual LV-to-MV DCDC converters, Common MV inverter
   8 X 0.6 MW DCDC converter form ~700 V to 6 kVDC,
   MVDC Common Bus,
   1 X 4.8 MW inverter to 4160 VAC
   - Reduces number of MV inverters but MV inverter current to 1000 A
   - Requires high voltage gain DC-DC converter

2) Series voltage-isolated LV-DC regulators, Common MV inverter
   8 X 0.6 MW voltage-isolated 750 VDC provides 6 kVDC,
   1 X 4.8 MW inverter to 4160 VAC
   - Reduces number of MV inverters but MV inverter current to 1000 A
   - Requires high-voltage isolation for 750 VDC regulator

High Power Architectures (Continued)

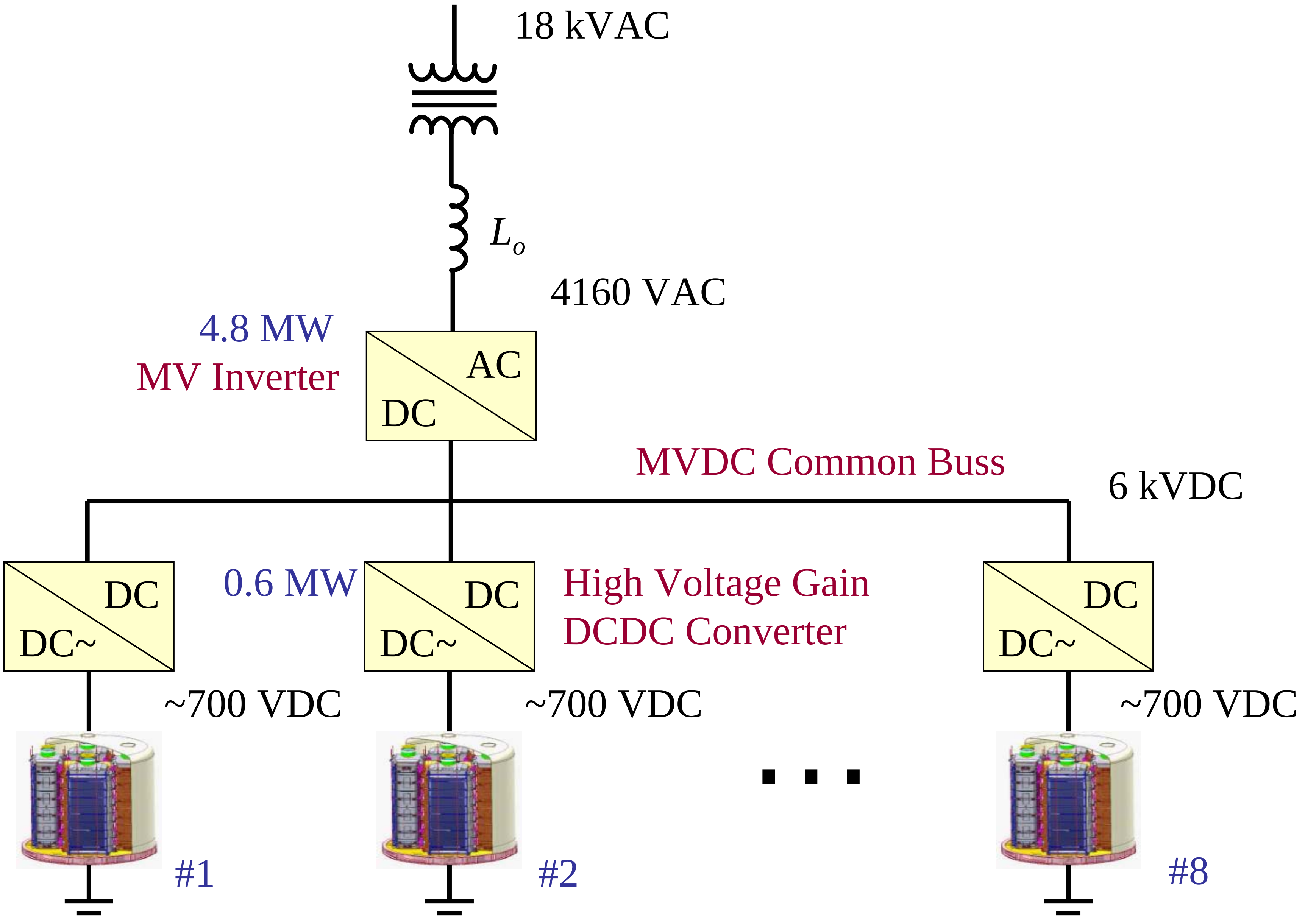
(8 X ~700 VDC FC to 4160 VAC)

3) Cascade: Series-connected voltage-isolated LV-DC regulators, with low frequency phase-interleaved inverters

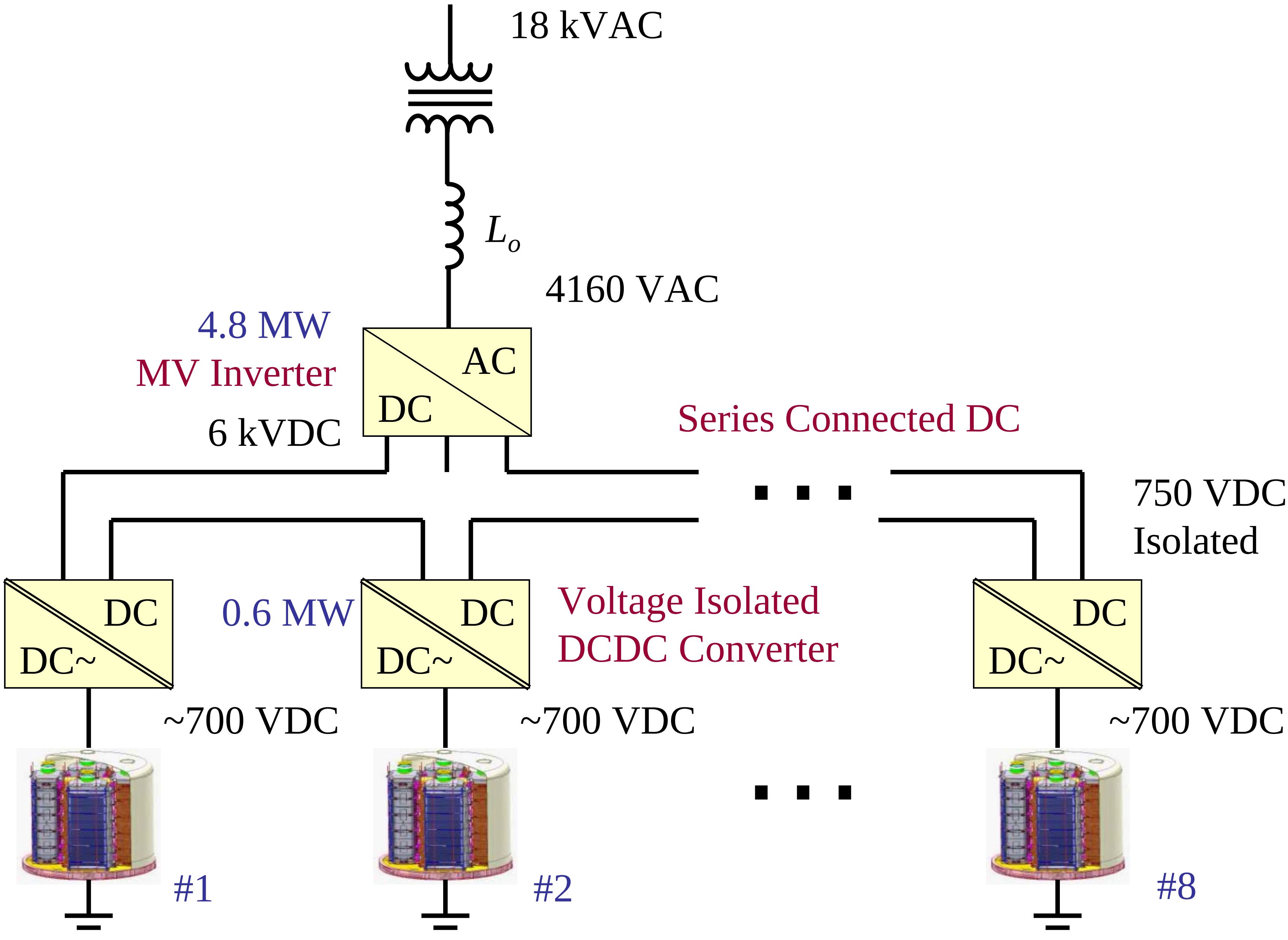
8 X 0.6 MW voltage-isolated 750 VDC regulators
series 8 X 750 V, 2.5 kHz phase interleaved inverters

- Uses 1200 V, 1000 A semiconductors to produce 4160 VAC
- 2.5 kHz switching provides effective 20 kHz
- improves tradeoff between switching loss and filter size
- Requires high-frequency, high-voltage isolation for 750 VDC regulator

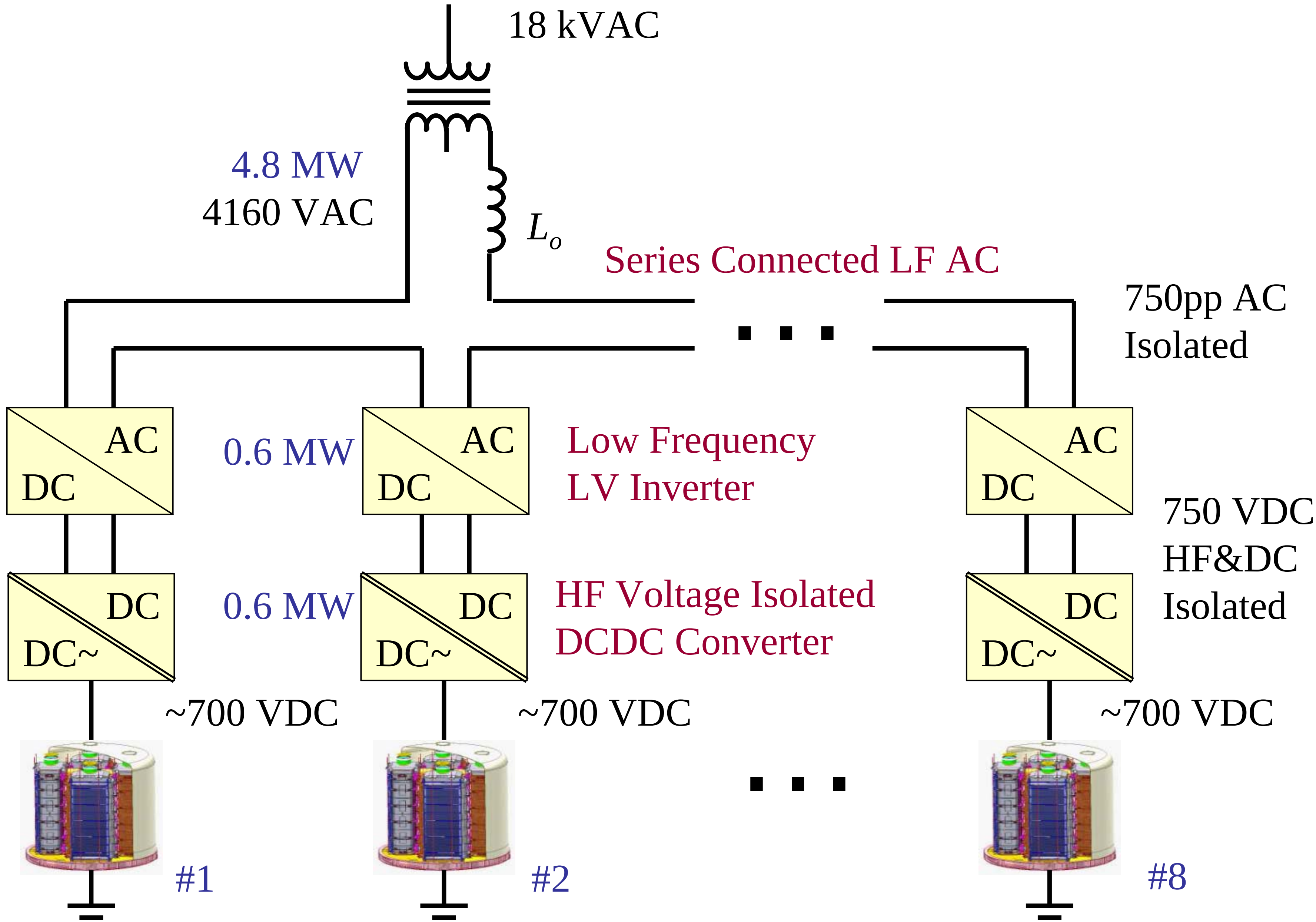
1) Individual LV-to-MV DCDC converters, Common MV inverter



2) Series connected, voltage-isolated LV-DC regulators, Common MV inverter



3) Cascade: voltage-isolated LV-DC regulators with phased interleaved LV inverters



Outline

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IV. Inputs from High-MW community

Needed:
Inputs from High MW Community

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

Session 4a

Enjeti

High-Megawatt Converter Technology Workshop for Coal-Gas Based Fuel Cell Power Plants

January 24, 2007 at NIST

Dr. Prasad Enjeti

TI Professor

Power Electronics Laboratory

Texas A&M University

College Station, Texas

Email: enjeti@tamu.edu

Introduction

- Fuel cells have been recognized as one of the most promising clean energy sources for power generation.
- High temperature fuel cells such as solid oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC) have been shown to be over 60% efficient at 500kW rating and above.
- Since the voltage produced by each cell is around 0.6 V DC many cells need to be stacked in series

Dimensions	
Height	27.5'
Width	49.4'
Length	59.6'

Features	Benefits
2000 kW net	Clean energy
480 VAC, 50 or 60 Hz	Efficient
By-product heat availability	Easily sited
Modular and scalable	Quiet Operation
Internal fuel reforming	High-quality power
Few moving parts	
Small package	
Fuel-flexible	

Emissions	
NOx	< 0.3 ppmv
SOx	<0.01 ppmv
CO	<10 ppmv
VOC	<10 ppmv

Available Heat	
Exhaust Temperature	≈650° F
Exhaust Flowrate	27,200 lbs/hr
Exhaust Heat Available	≈2.8 mm Btu/hr.

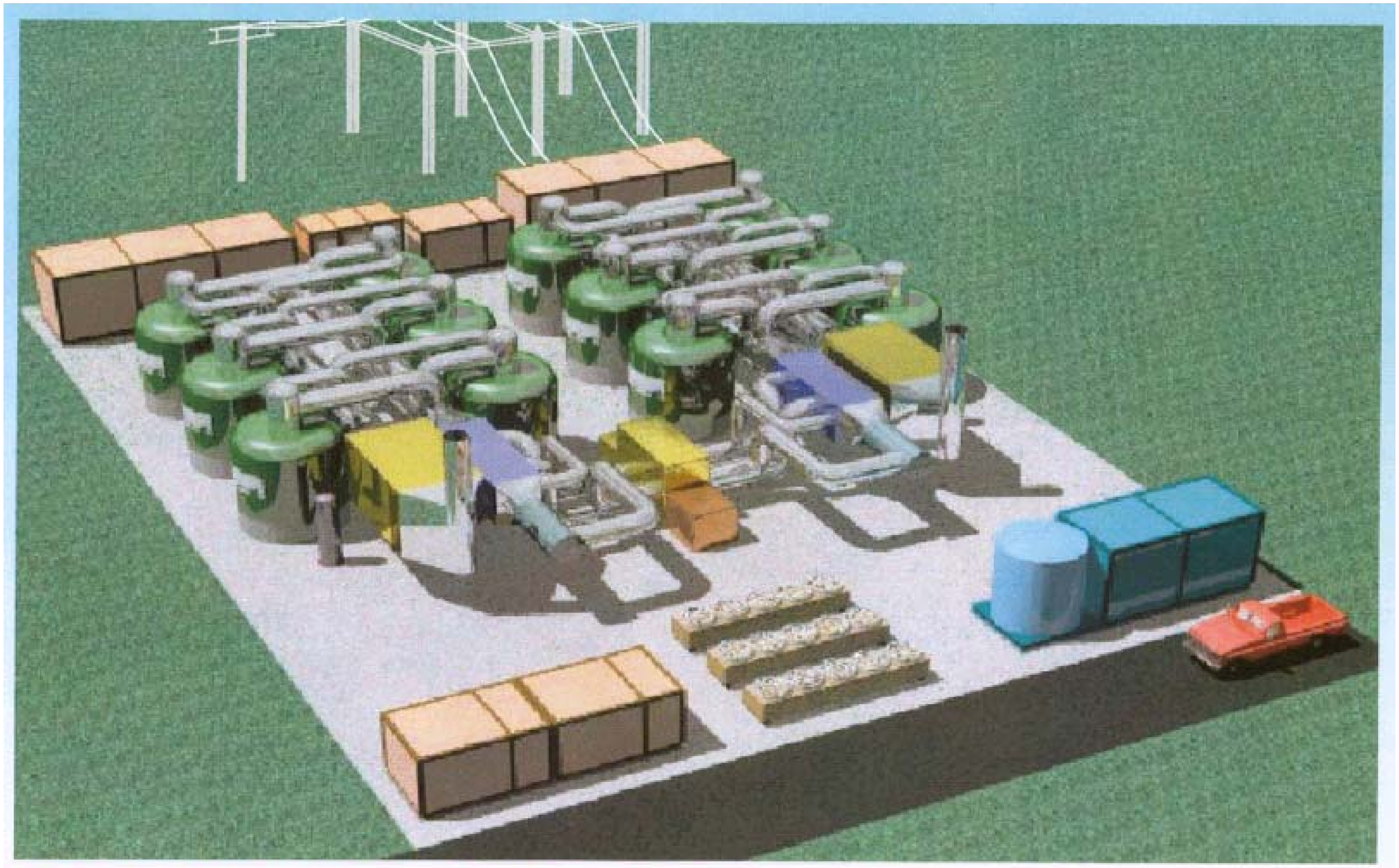
DFC 3000, 2MW Fuel Cell Plant
Fuel Cell Energy Inc.

A 250kW PSOFC / MTG System

Figure 1. The SWPC 220 kW PSOFC/MTG

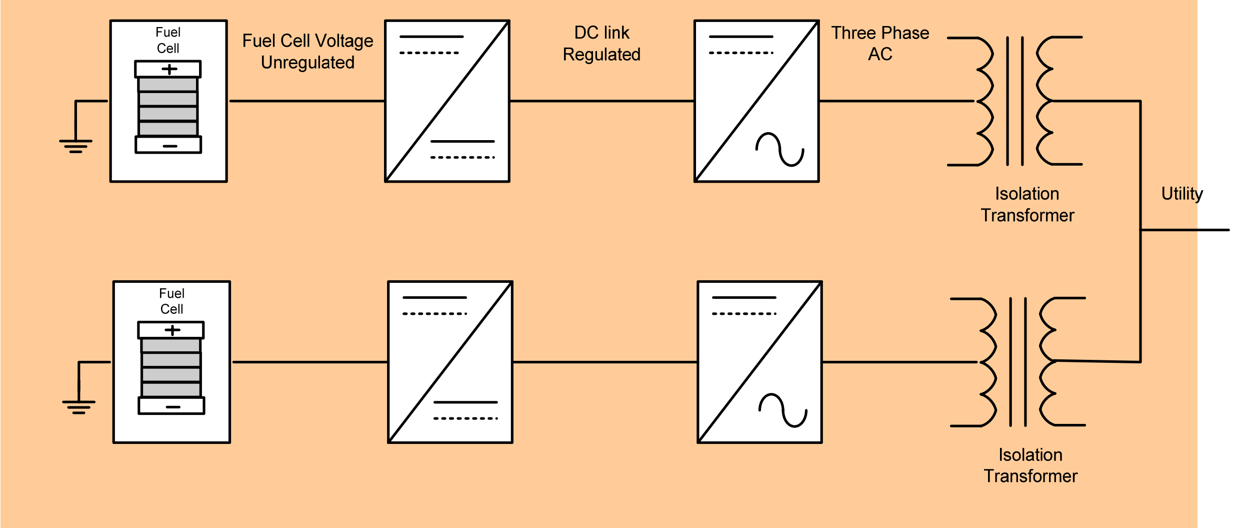
A Direct Fuel Cell Turbine Hybrid

by: Fuel Cell Energy Inc.

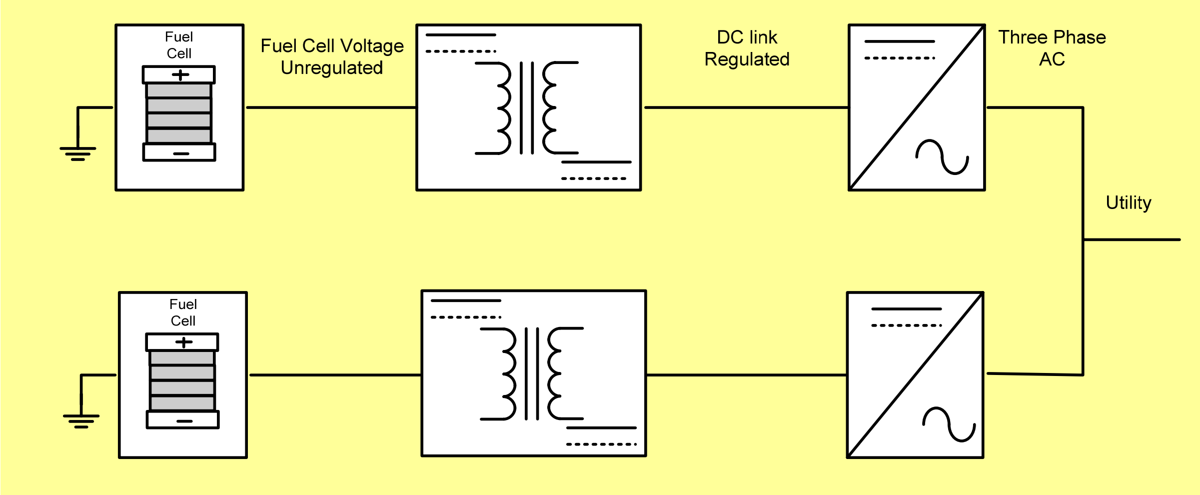


20 MW HIGH EFFICIENCY DFC®/TURBINE HYBRID POWER PLANT

Multi Stack Fuel Cell Systems & Associated Power Electronics

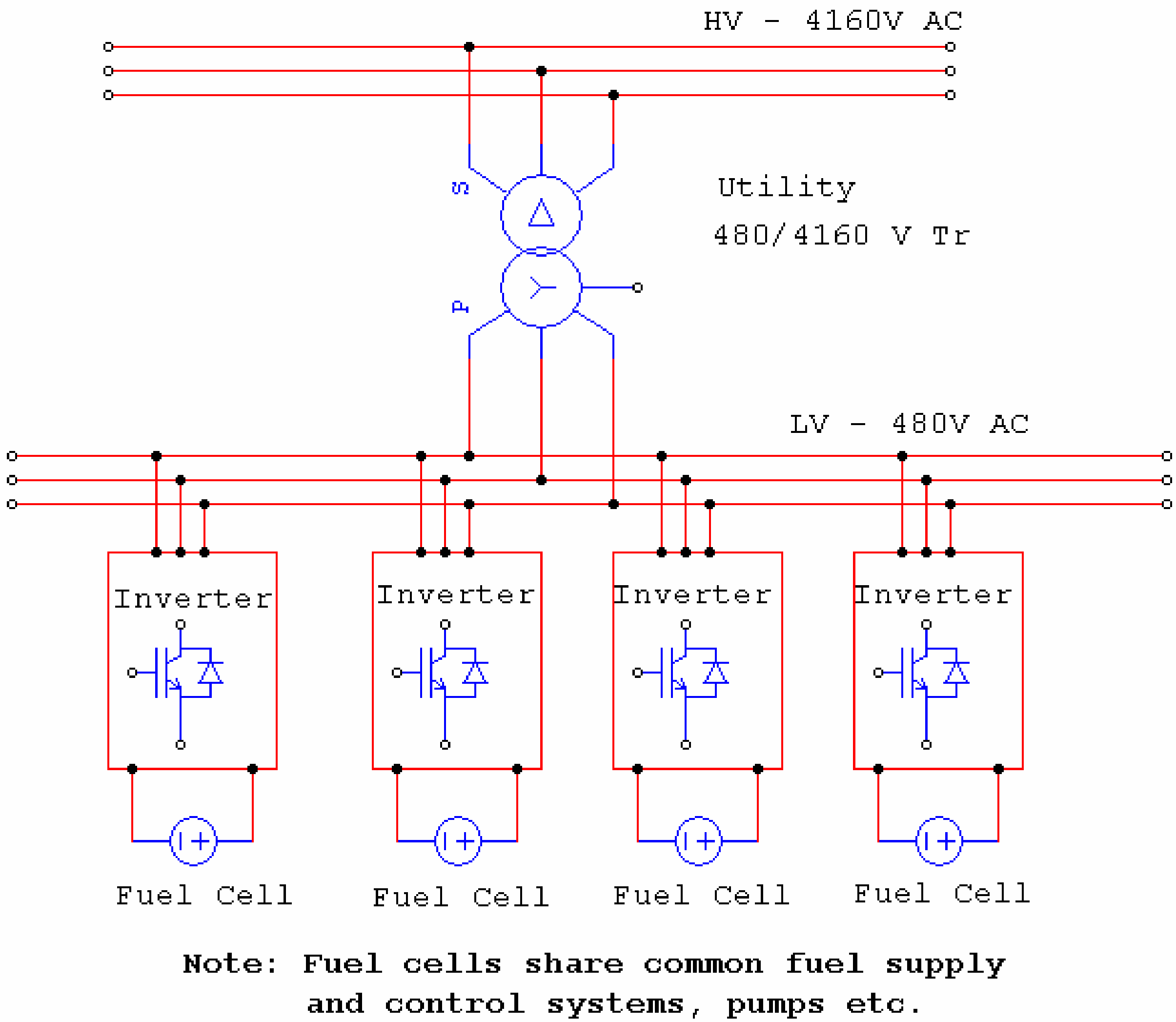


With 50/60 Hz Isolation Transformer



Without 50/60 Hz Isolation Transformer

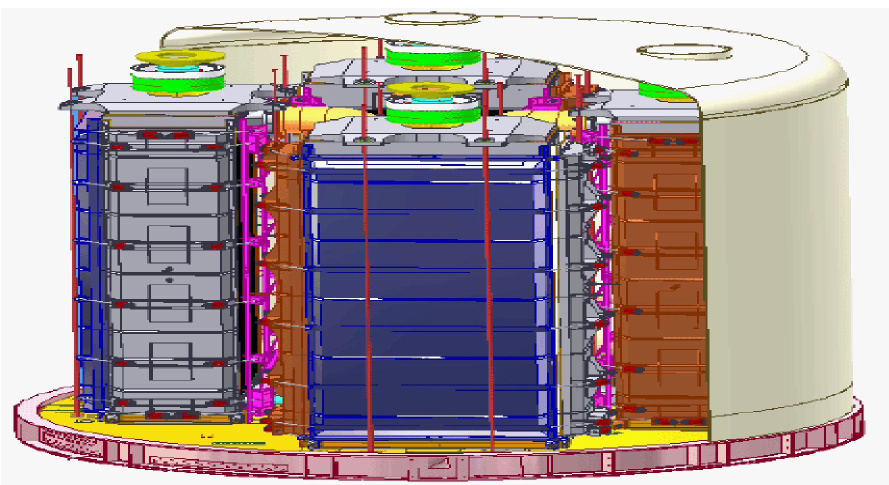
Standard Power Conversion Topology # 1

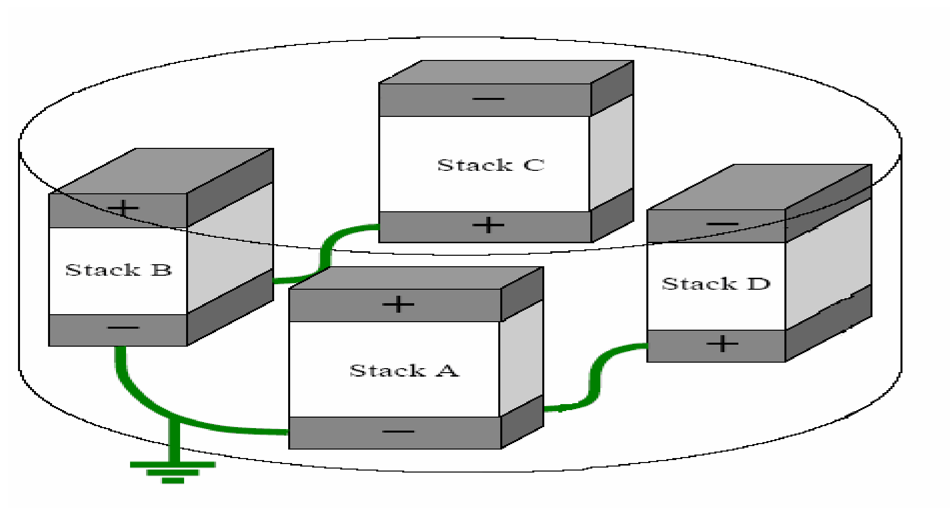


- **Each Fuel Cell & its Inverter is rated for say 300kW**
- **Inverters employ 1200V Si or SiC devices**
- **Modular system**
- **Fuel Cells can share a common fuel supply, heat exchangers etc.**
- **Failure in power electronics and/or a fuel cell only disables one unit**

Fuel Stack Voltage Limitation

- Since each cell produces only 0.6V, there is a maximum number of cells that one can stack before thermal/water management issues can be safely managed. In addition, electrostatic potential to ground within the fuel cell stack needs to be limited for safe operation
- **Considering the above factors the maximum voltage that a fuel cell stack can safely produce is around 350V**





Commercially Available Medium Voltage Power Converters for Utility Applications

Applications of medium voltage converters

- **Medium voltage converters are mainly used in the industry for**

  - **Voltage disruption compensation**
    - **Dynamic Voltage Restorer – ABB**
    - **MegaDySC - Soft Switching Technologies**

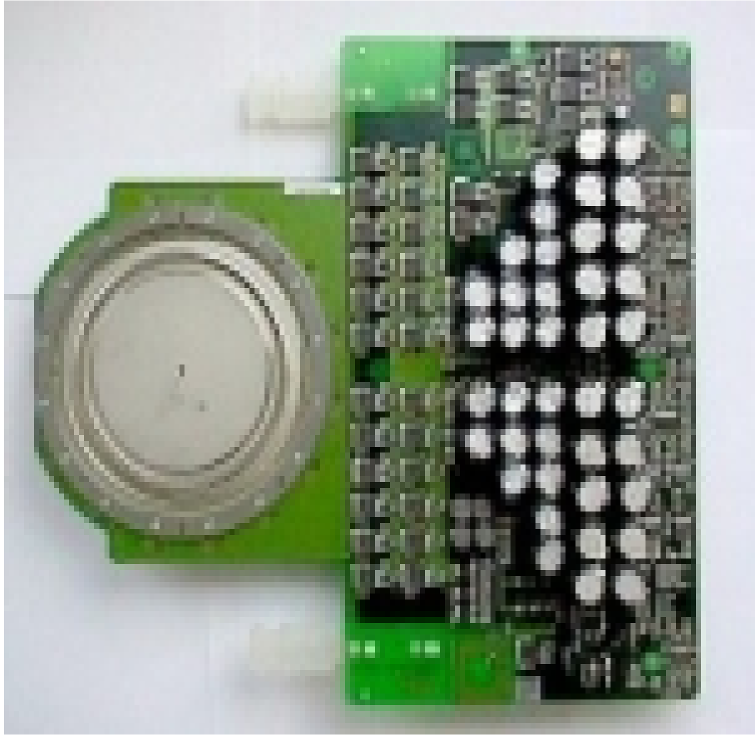
  - **Medium voltage ASD's**
    - **NPC Drives (IGCT's) - ABB**
    - **Series Connected 1-phase Inverters – GE Robicon - Toshiba**

Power Conversion for High Power Hybrid Fuel Cell / Turbine System

Feature	IGBT	GTO	IGCT
device on-state loss	100 %	70 %	50 %
device turn-off loss	100 %	100 %	100 %
device turn-on loss	100 %	30 %	5 %
gate drive power	1 %	100 %	50 %
short-circuit current	self limited (= f(t))	external (choke)	external (choke)
dv/dt snubber	no	yes	no
di/dt snubber	no	yes	yes
switch chip	discrete	monolithic	monolithic
diode chip	discrete	monolithic	monolithic
chip mount	solder	pressure	pressure

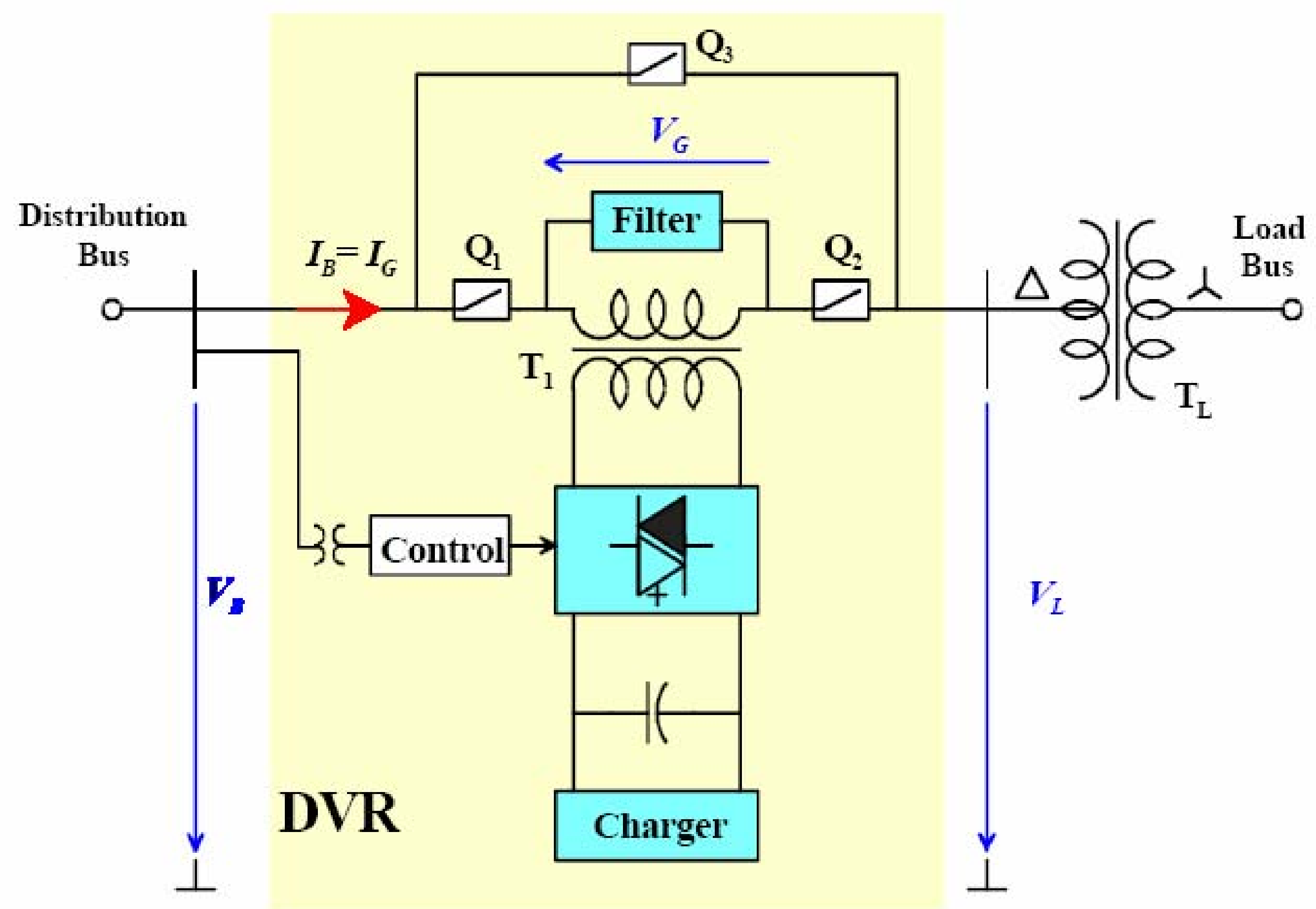
Power Conversion for High Power Hybrid Fuel Cell / Turbine System

IGCT – Integrated gate commutated thyristor (ABB)

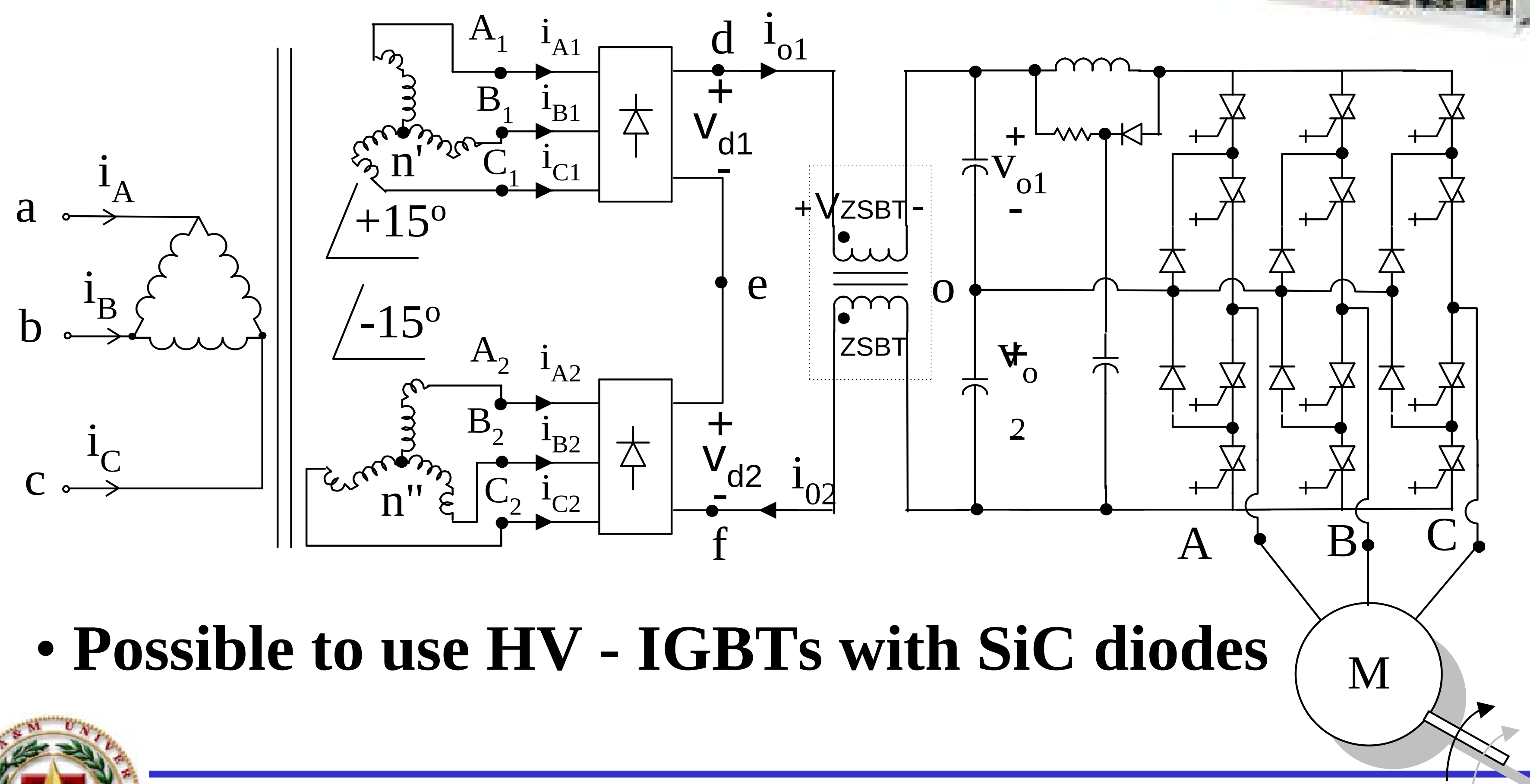


The ACS 1000 is the first drive to use a new power semiconductor switching device called IGCT (Integrated Gate Commutated Thyristor). This advanced, high-power semiconductor approaches the "ideal switch" for medium-voltage applications. IGCT brings together a versatile new power handling device, the GCT, (Gate Commutated Thyristor) and the device control circuitry in an integrated package.

Medium voltage DVR - ABB

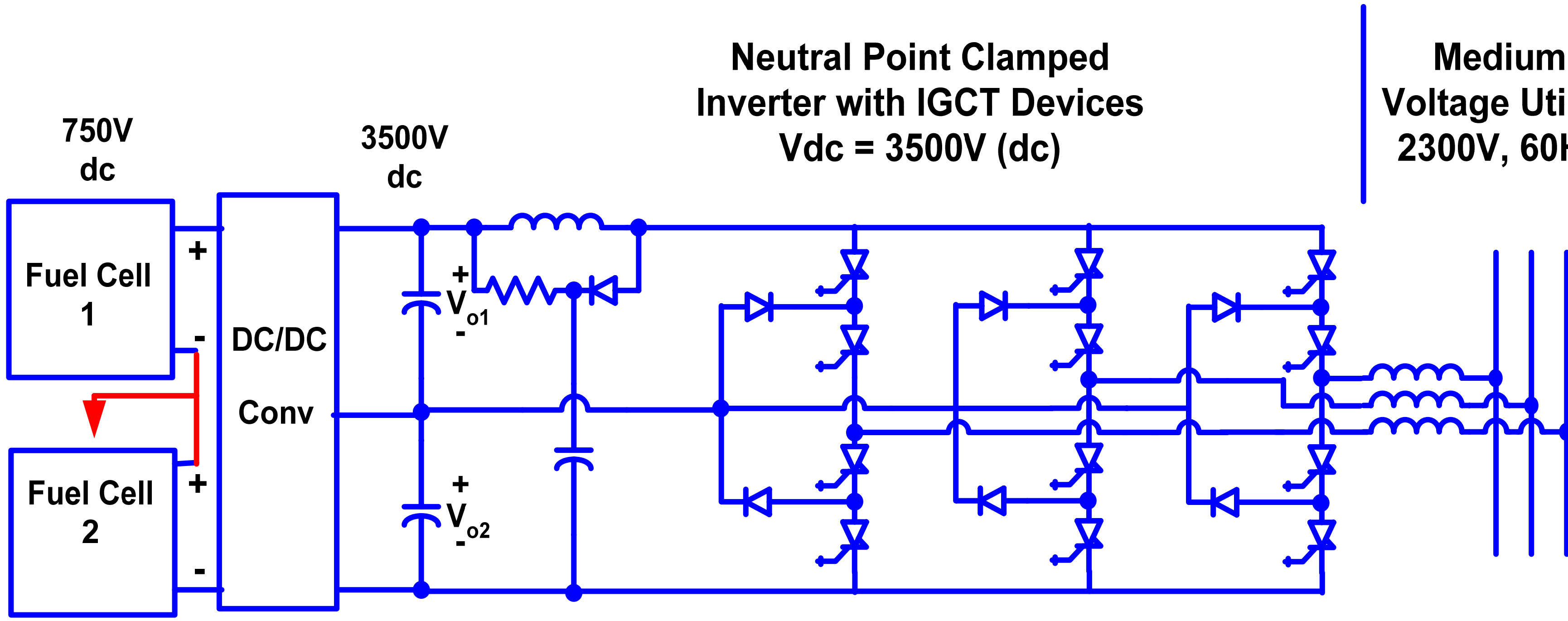


Medium Voltage Adjustable Speed AC Motor Drive – ABB: ACS 1000, Silcovert – ASI-Robicon
Vout: 4kV; Po = 12 MW



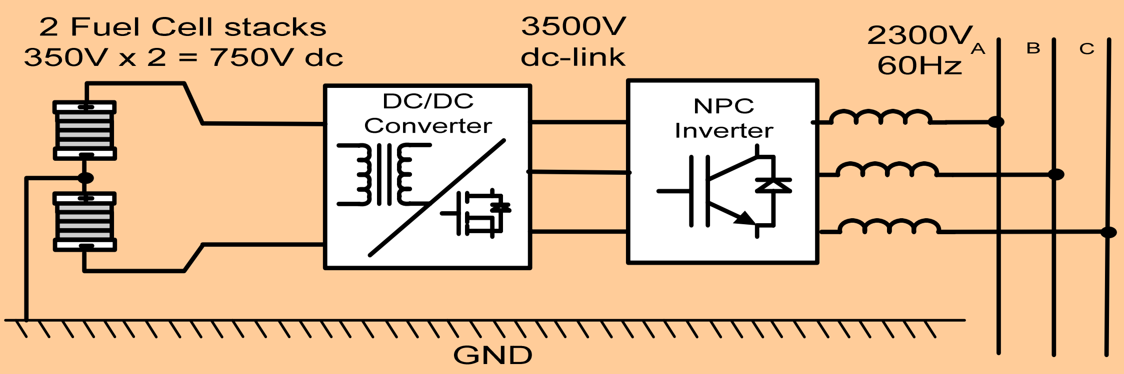
- **Possible to use HV - IGBTs with SiC diodes**

Power Conversion Topology # 1
For Utility Interface of Fuel Cell Systems



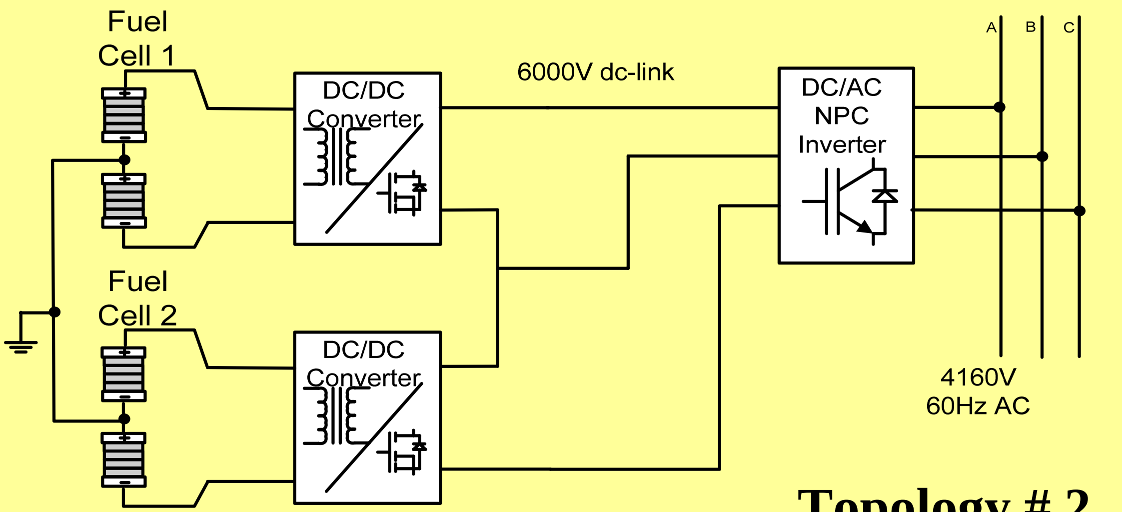
- **IGCT / IGBT devices are available in higher voltage and current ratings**
- **3 level PWM output voltage is high quality & suitable for 4160V, 60Hz utility interface**
- **Each fuel cell stack voltage does not exceed 350V (dc)**

Multi Stack Fuel Cell Systems & Associated Power Electronics



Topology # 1

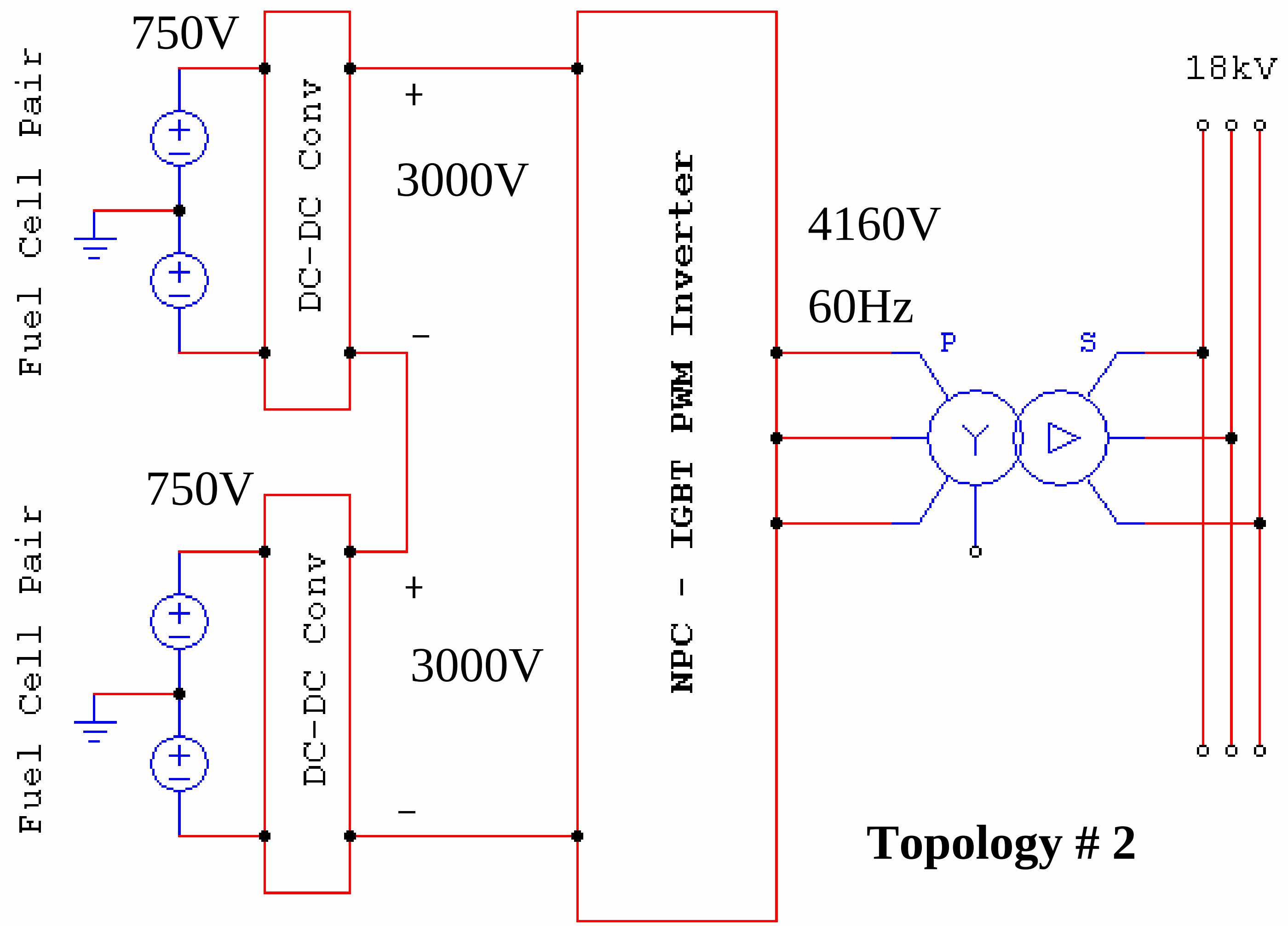
- Two stack fuel cell systems with a high frequency DC-DC converter and DC-AC Inverter
- One dc-dc converter one Inverter for one pair of fuel cell stack: IGBT or IGCT Inverter



Topology # 2

- Four stack fuel cell systems with two cascaded high frequency DC-DC converter and one DC-AC Inverter is employed
- Each fuel cell stack is subjected to a maximum voltage of 350V
- Topology offers control flexibility of fuel cell stack pairs. Control of dc-dc converters is possible to allow each pair of fuel cell stacks to supply different output power

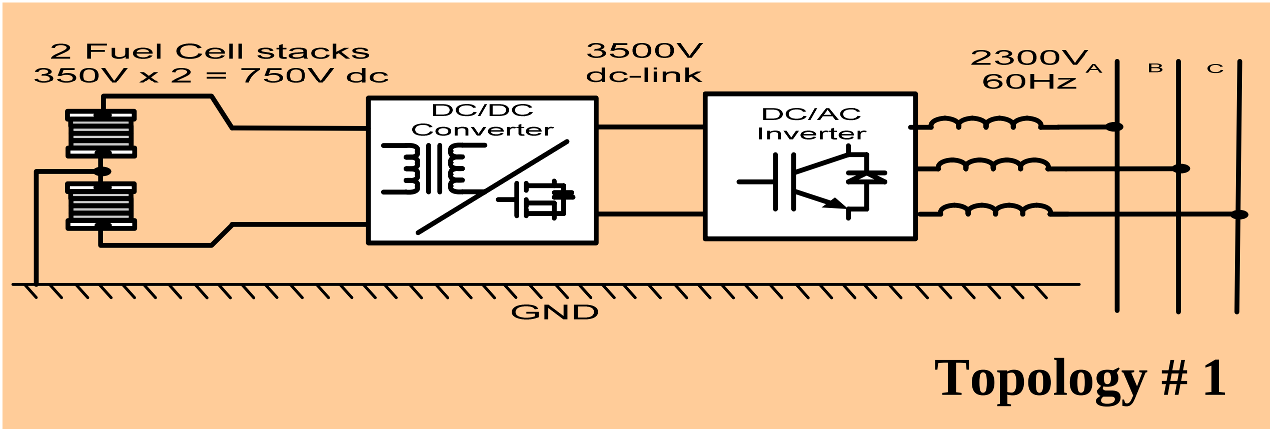
Multi Stack Fuel Cell Systems & Associated Power Electronics

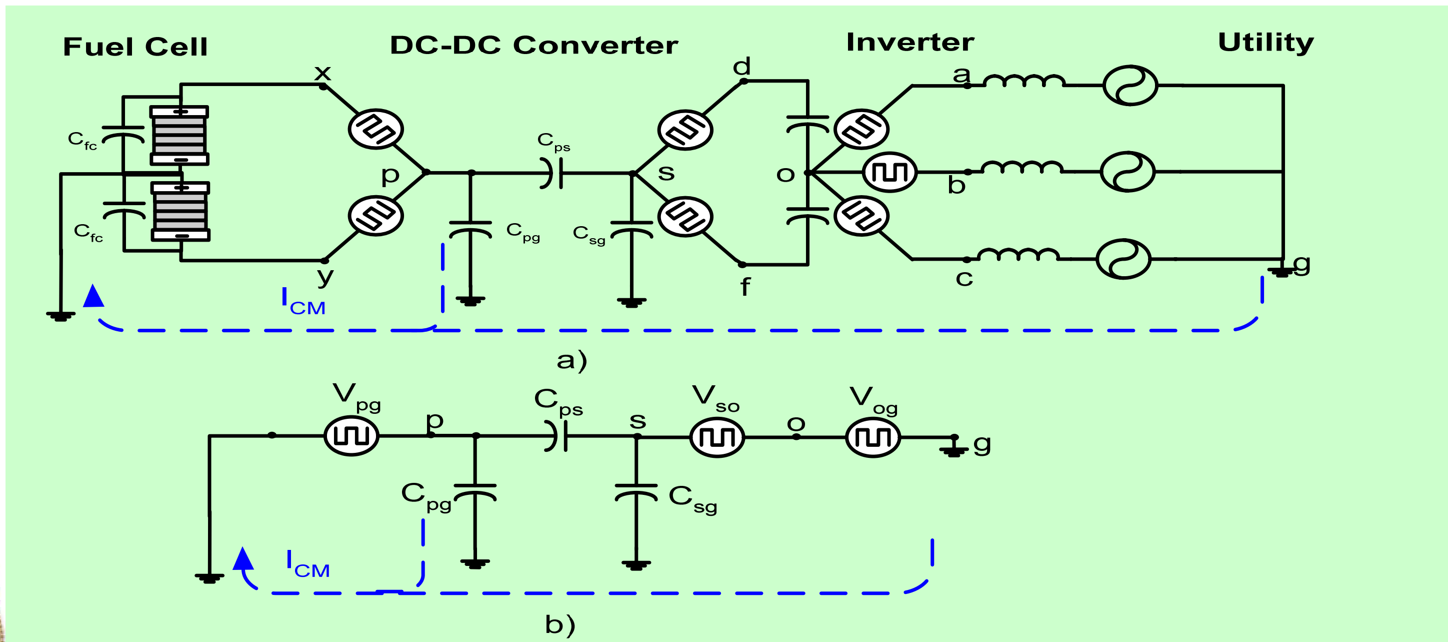


Topology # 2

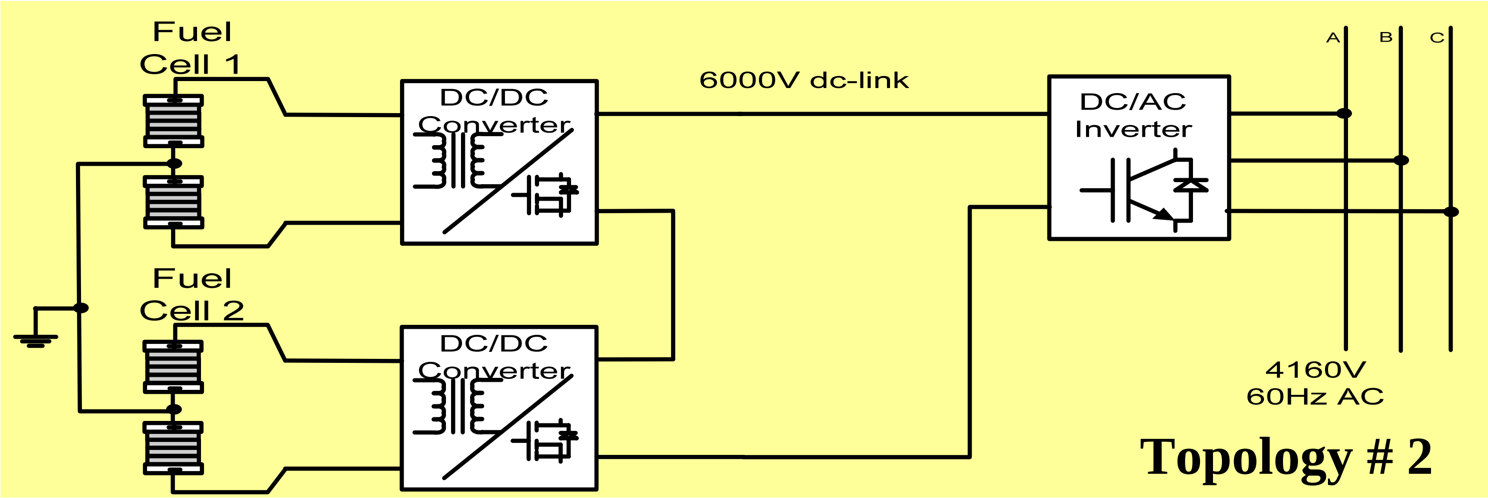
Additional Considerations: Common mode currents

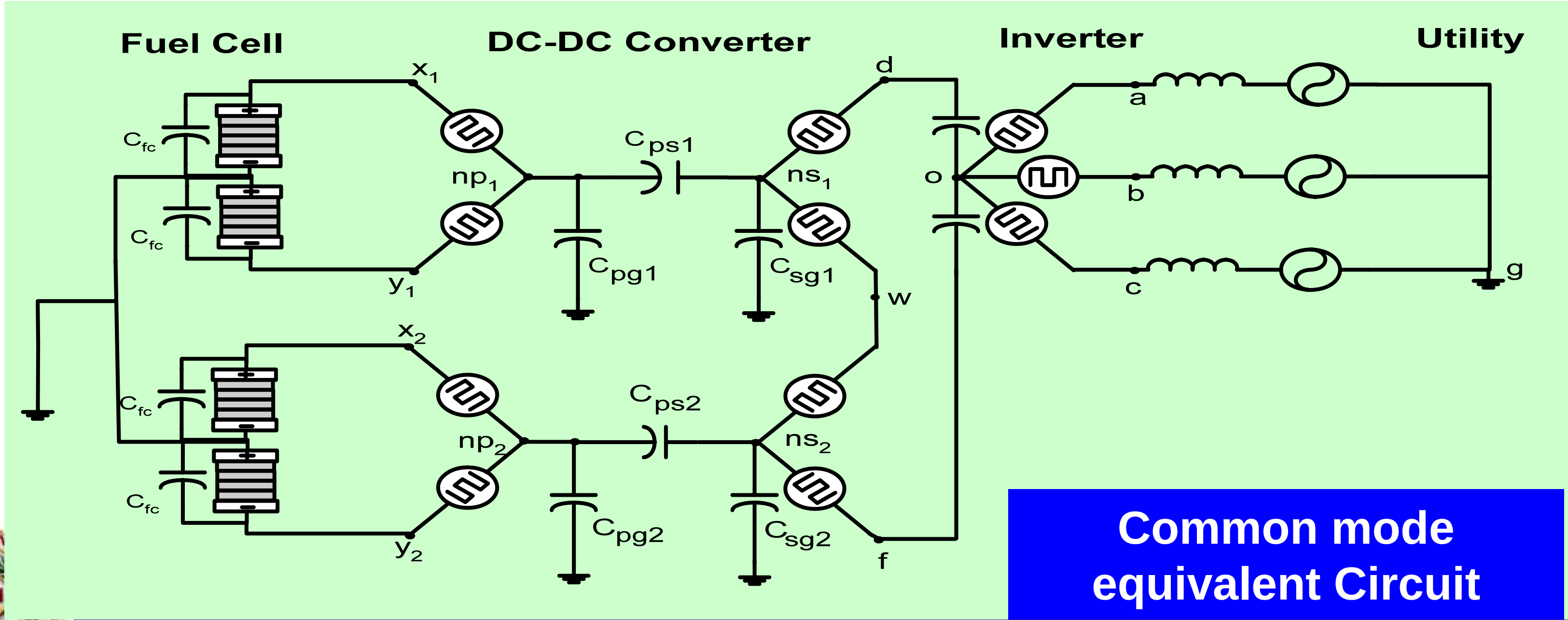
- **The transformer in the DC-DC converter is modeled by lumped capacitances from primary and secondary to ground, and a capacitance from secondary to primary**





Additional Considerations: Common mode currents

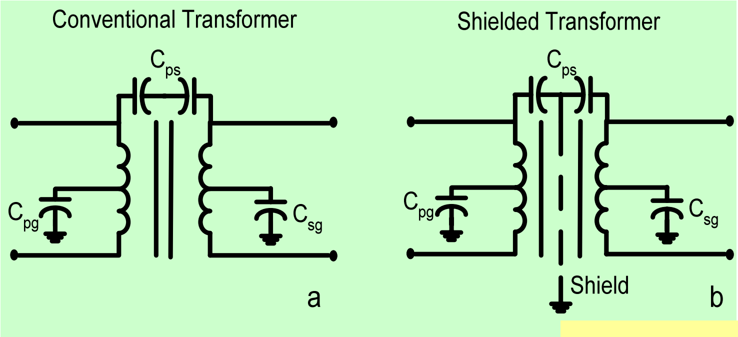


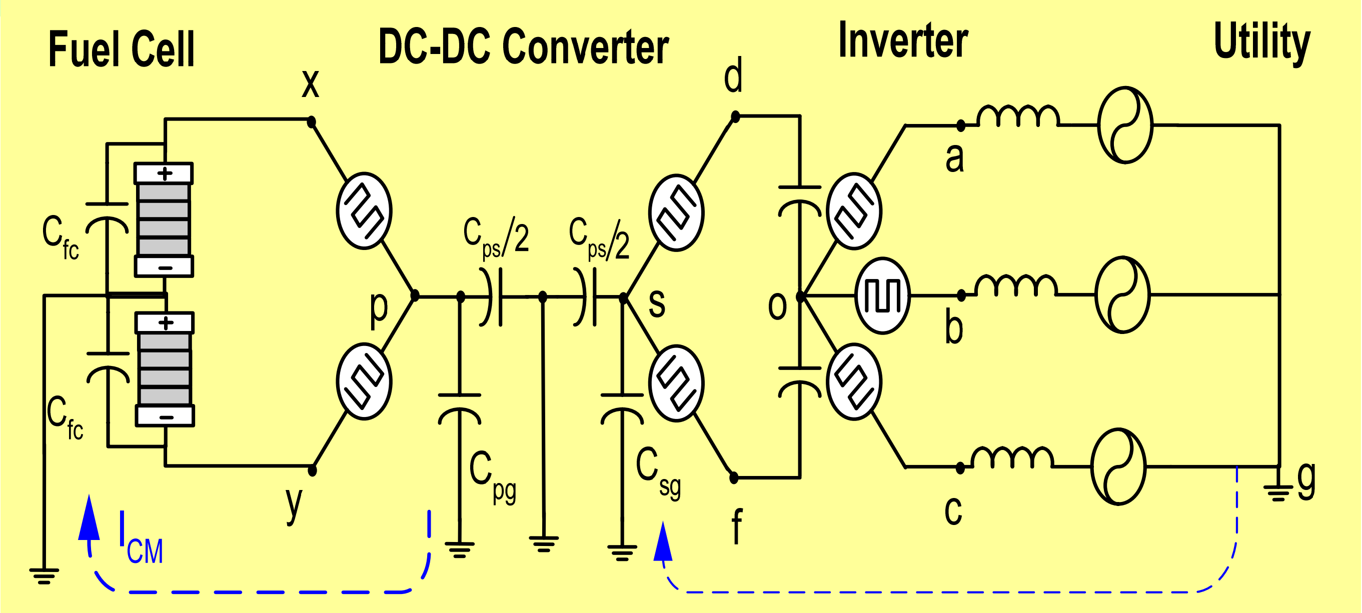


Common mode equivalent Circuit

Multi stack DC-DC converter and inverter analysis

- **A shielded transformer is proposed to isolate the interaction between the DC-DC converter & Inverter stages**

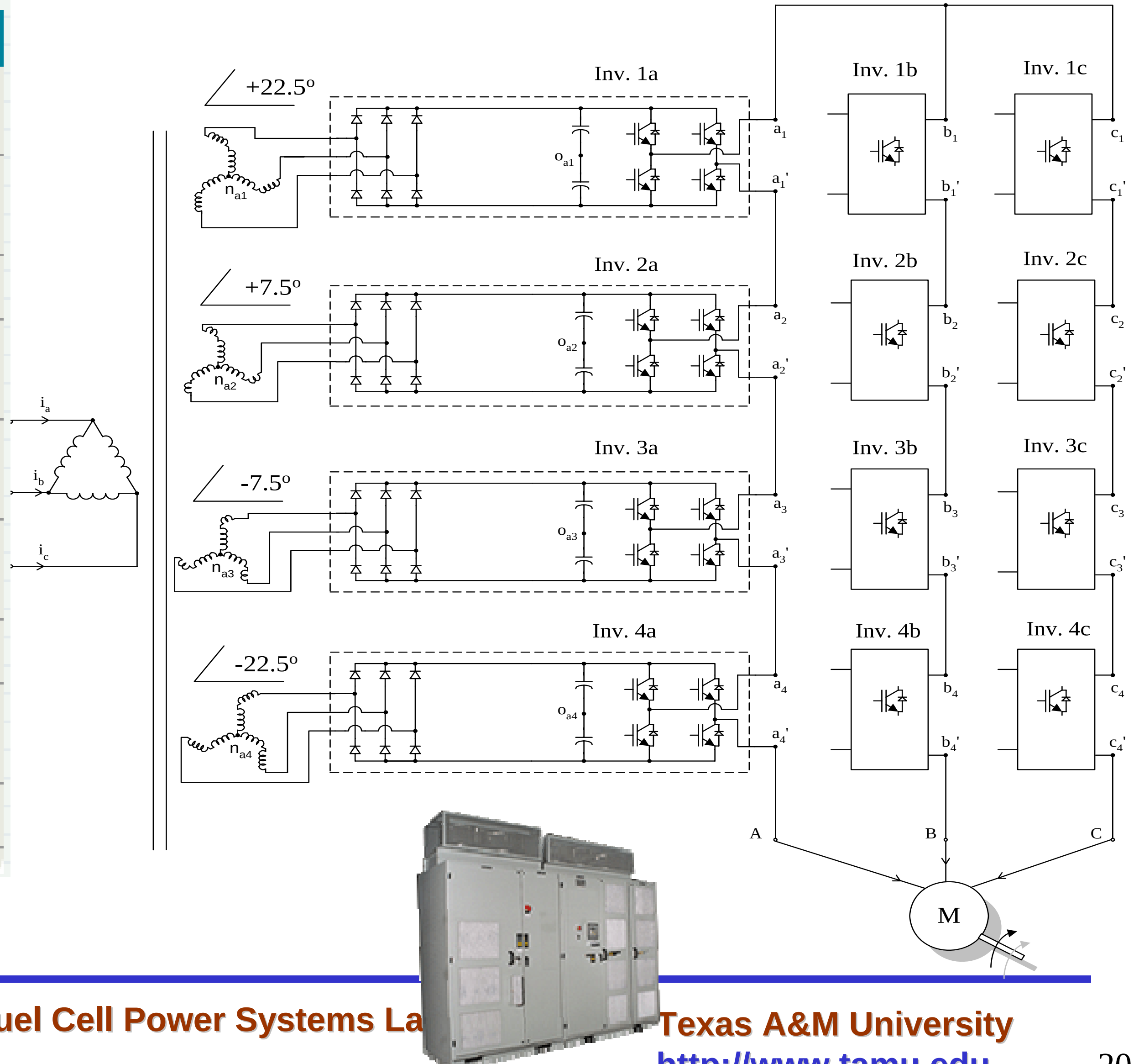




- **To further reduce Icm a common mode filter needs to be installed at the output of the DC-DC Converter**

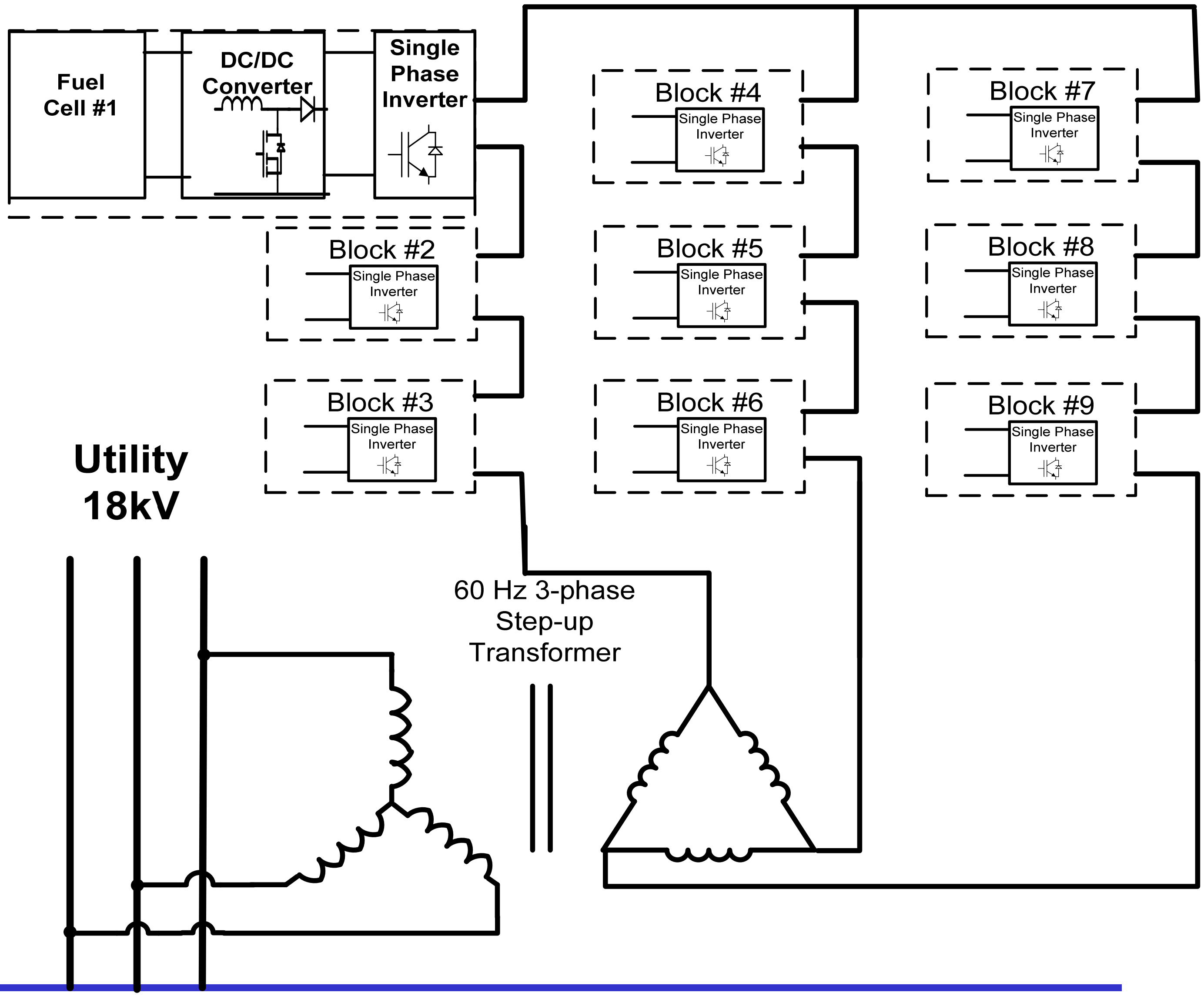
Medium Voltage Adjustable Speed AC Motor Drive: ASI-Robicon – Perfect Harmony

SPECIFICATIONS	
Power Range:	300 kW - 75 MW
Output Voltage:	2300 - 13800 VAC
Motor Voltage:	2.3 - 13.8 kV
Motor Power Range:	300 kW - 32 MW 225 - 43000 HP
Continuous Power Range:	290 kVA - 35 MVA
Rated Output Current:	70 - 1400 A
Topology:	Multi-level PWM
Power Device:	Voltage Source IGBT
Output Frequency:	0 - 330 Hz



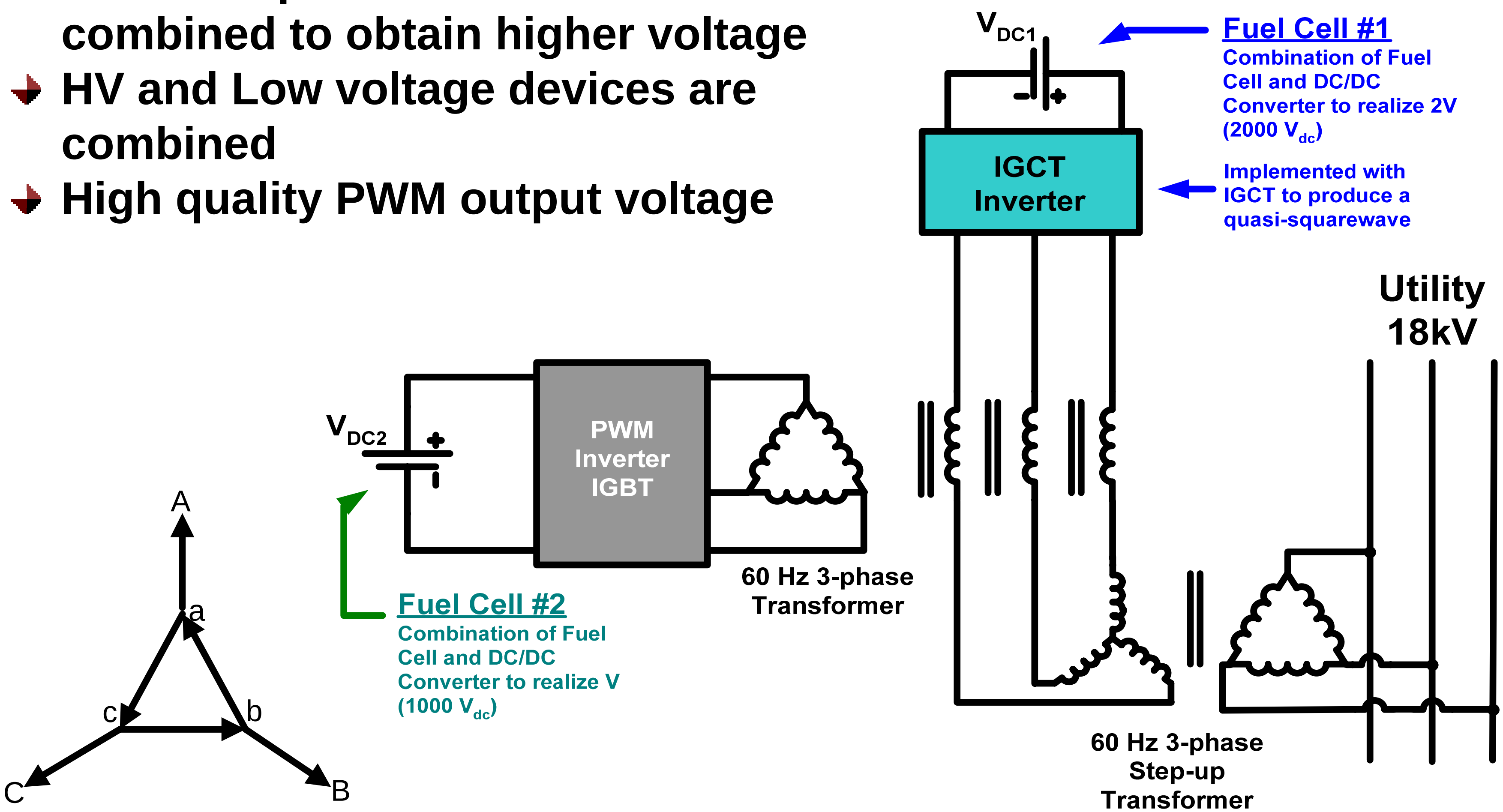
Power Conversion Topology # 3

- **Modular 1-phase converters can be connected in cascade to realize higher output voltage**
- **Advantage: Lower voltage power electronics**
- **Disadvantage: Common mode elevation of different fuel cell stacks may be unacceptable**



Power Conversion Topology # 4

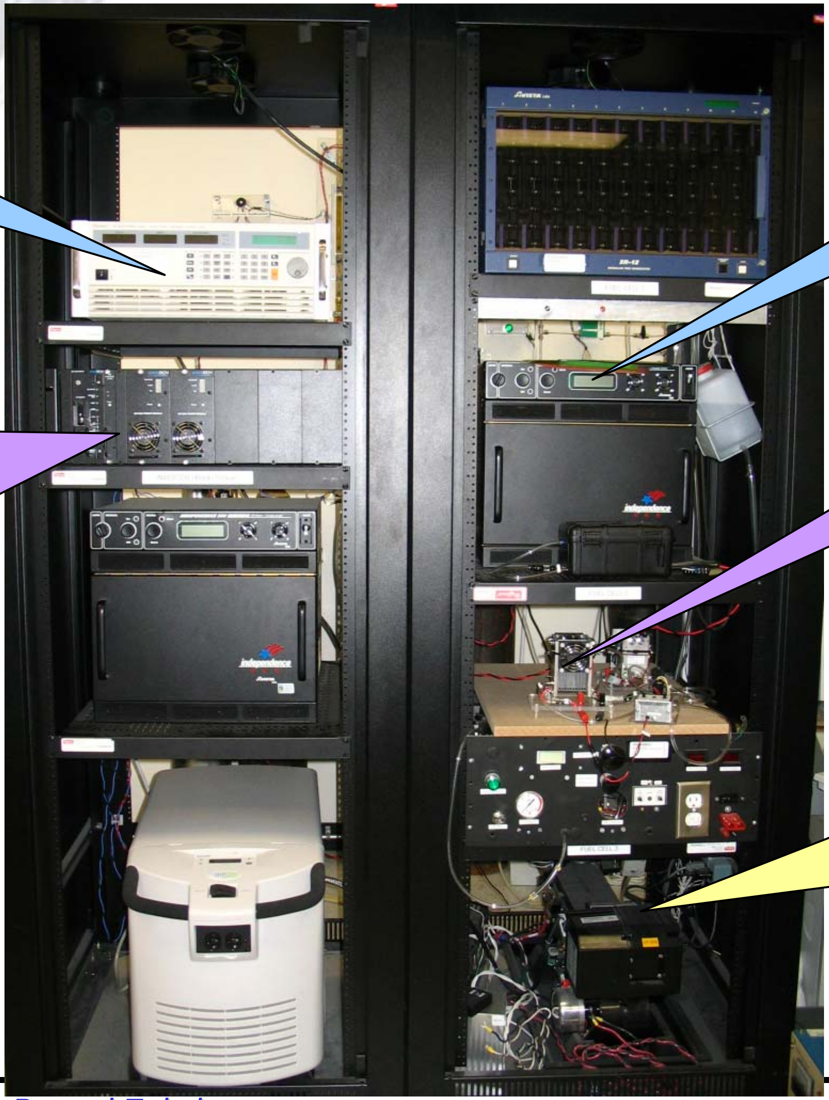
- Several 3-phase converters can be combined to obtain higher voltage
- HV and Low voltage devices are combined
- High quality PWM output voltage



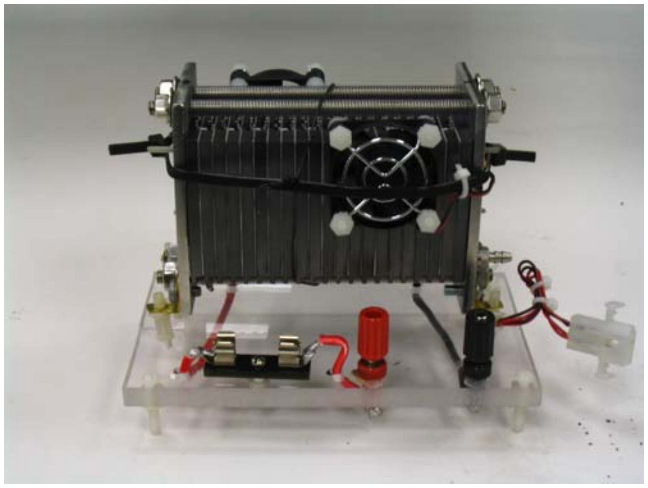
Comparison of Power Conversion Topologies

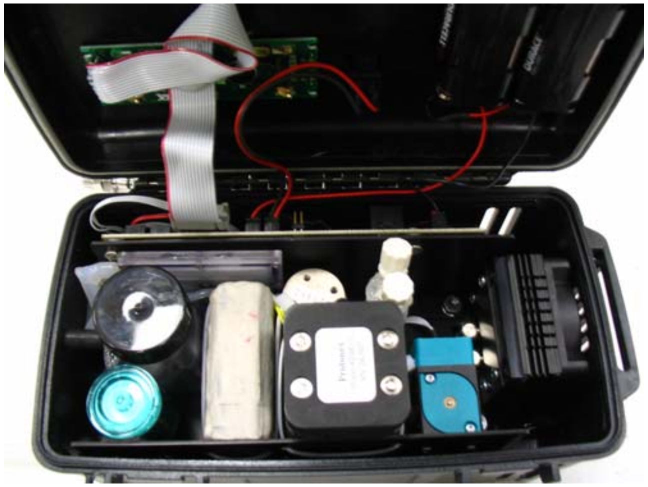
Topology # 1	**2 fuel cell stacks (350V) series connected & center point grounded, one dc-dc converter followed by a 3-level inverter to produce 2300V 3-phase ac**
Topology # 2	**4 fuel cell stacks (350V) series connected in pairs and center point grounded, two dc-dc converters with outputs connected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

Fuel Cell Applications Laboratory in Dept of Electrical & Computer Engineering



Small Fuel Cells: 20W to 50W Systems





Questions ?

Session 4a

Lai

Multilevel Converters for Large-Scale Fuel Cell Power Plants

DOE Workshop on Development of Large Scale Inverters Systems (>100 MW) for Coal-Gas Based Fuel Cell Power Plants

Gaithersburg, MD

January 24, 2007

Dr. Jason Lai
Virginia Tech
Future Energy Electronics Center
Blacksburg, VA 24061-0111

Outlines

- **Technical Issues and State-of-the-Art Large-Scale Power Electronics**
- **Configurations of Fuel Cell Power Conditioning Systems**
- **Multilevel Converter Based Fuel Cell PCS**
- **Control of Paralleled Inverters**
- **Device Requirements**
- **Summary**

Photograph: a 400-kW current source DC-DC converter

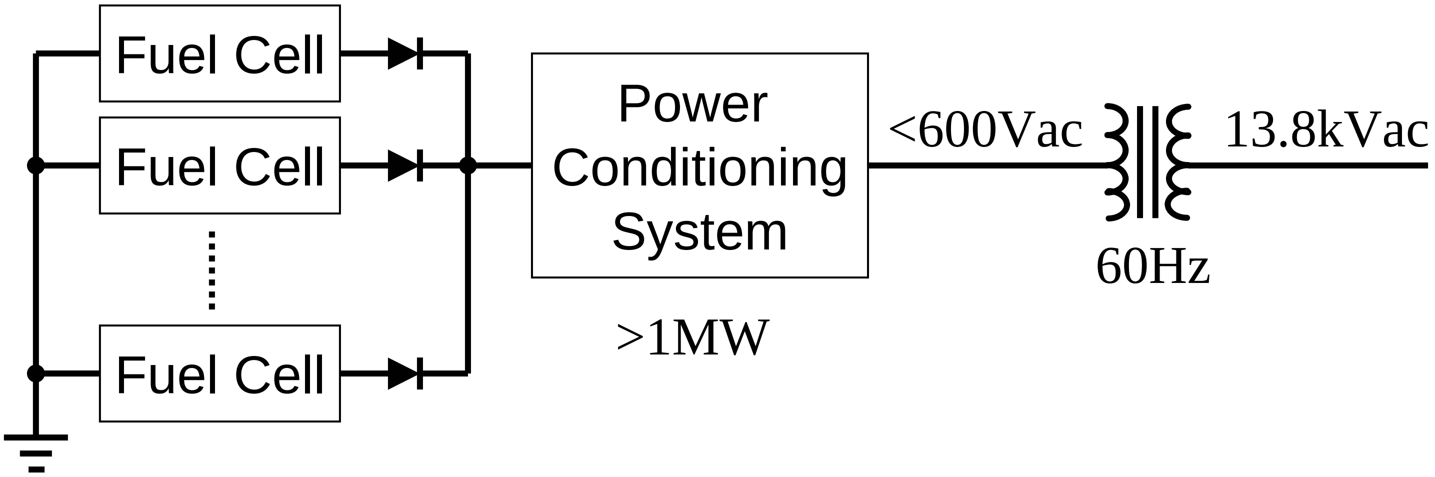
Issues

- **Parallel/Module size – what's the best size for a single module (1MW, 10MW, …, etc.)?**
- **Fuel cell voltage level – low-voltage stack versus high-voltage stack, what's the limit of fuel cell voltage level?**
- **Voltage stacking method – stacking fuel cells versus stacking converters, problem with common voltage.**
- **Semiconductor device – silicon versus silicon carbide, HV device versus LV device. What are needed?**
- **Circuit topology – voltage source versus current source converters, multilevel versus multiphase converters**
- **Fuel cell current ripple – potential problem with single-phase inverter induced fuel cell current ripples**

State-of-the-Art High Power Electronics

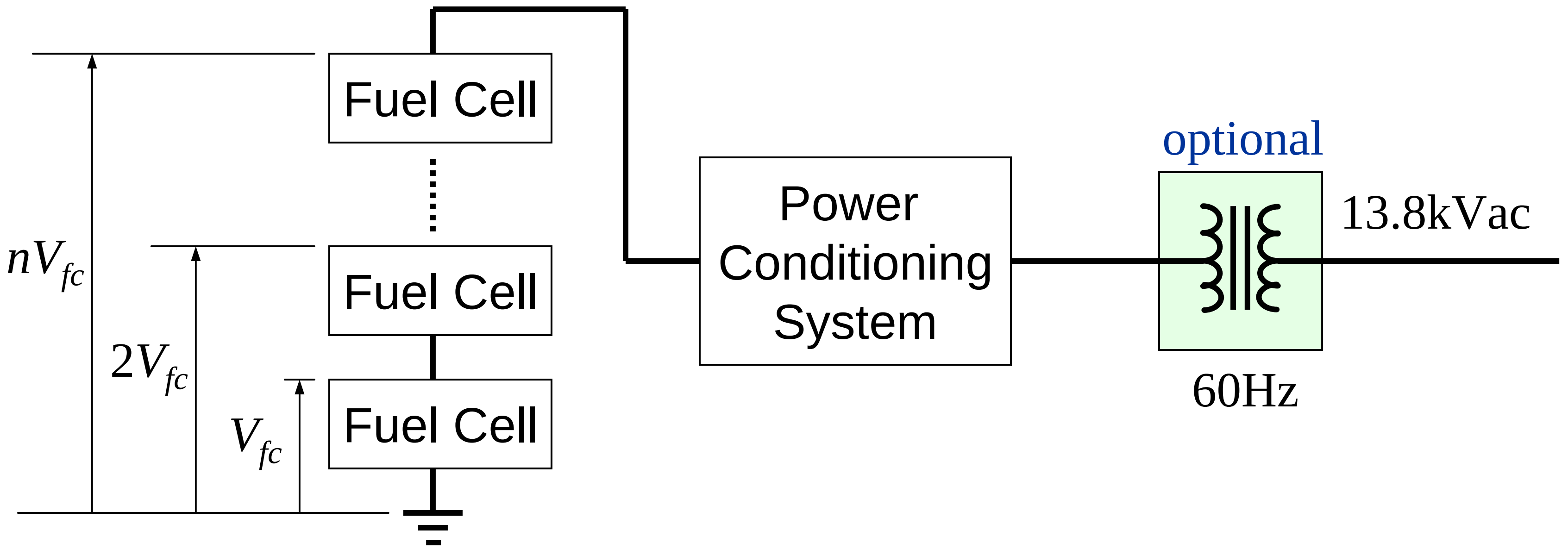
- **>1GW Level Pacific Intertie HVDC System**
  - **DC Link Voltage: ±500kV**
  - **Power Level: 3100MW**
  - **Circuit Topology: Current Source Inverters**
  - **Device: 6.5kV Thyristors stacked up for 133kV blocking**
  - **Switching Frequency: 60Hz**
  - **Problems: >5 acres of land for LC filters**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

Configuration with Paralleling Multiple Fuel Cells and a Large PCS



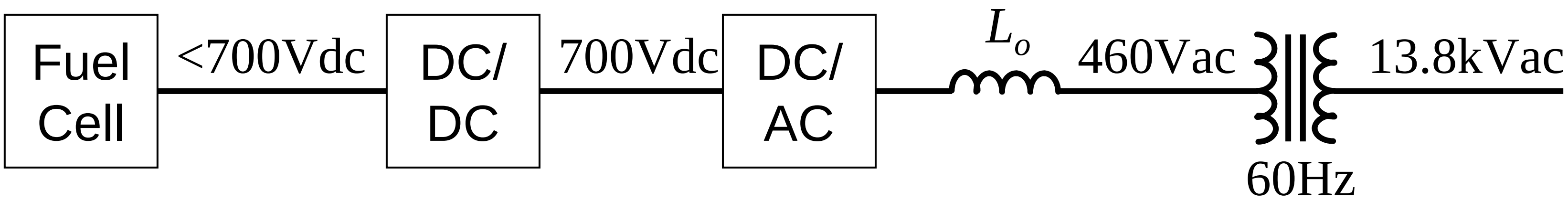
- **Multiple sub-MW fuel cells in parallel**
- **MW-level power conditioning system**
- **Low voltage power electronics**
- **Low frequency transformer (bulky, expensive)**
- **Need diode to block circulating current between fuel cells (lossy)**

Configuration with Series Connected Fuel Cells and a High-Voltage PCS



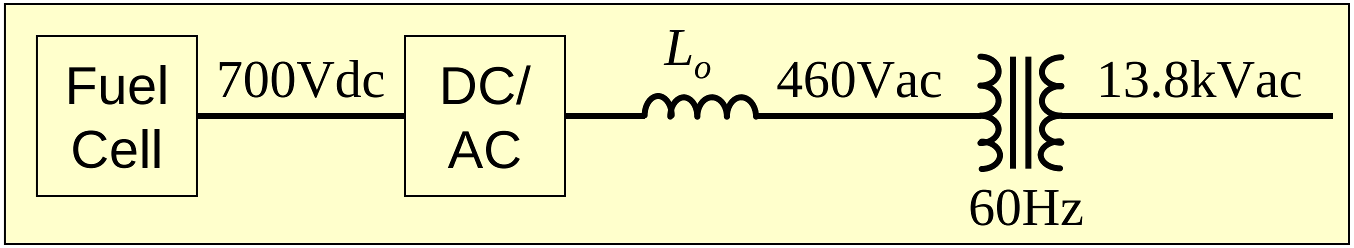
- Multiple fuel cells connected in series to obtain high voltage
- High voltage power electronics is needed
- Low-frequency transformation becomes optional depending on how high is the power electronics output voltage
- Problem is common-mode (CM) voltage of top level fuel cells

Low-Voltage Power Electronics Options



1. Fuel cell + DC-DC converter + DC-AC inverter + LF transformer

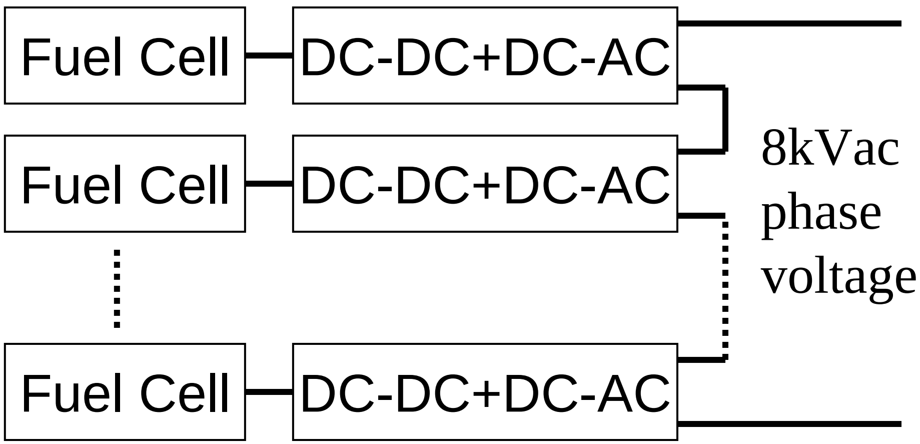
- Fuel cell independently sends power to grid regardless its output level
- Fixed dc bus allows output inductor L_o to be optimized

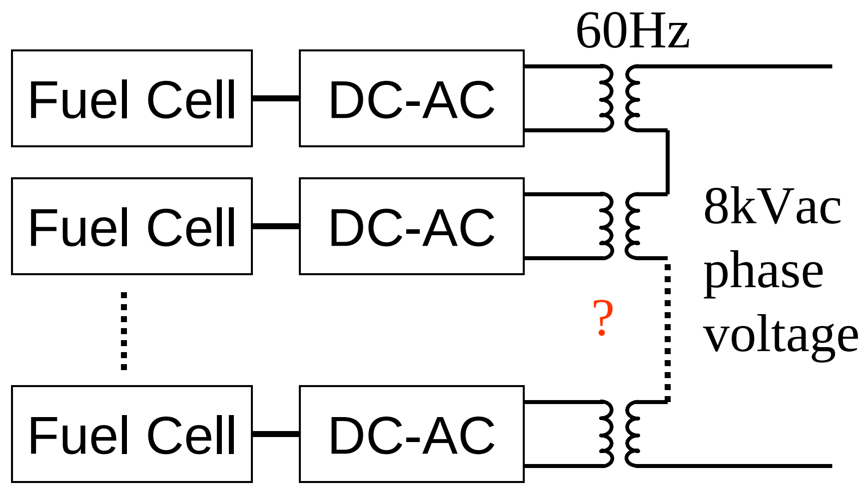


2. Fuel cell + DC-AC inverter + LF transformer

- Fuel cell sends power out only at sufficiently high enough output levels
- Variable dc bus needs large output inductor L_o

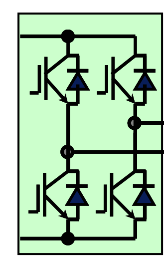
Options with Cascaded Multilevel Inverters



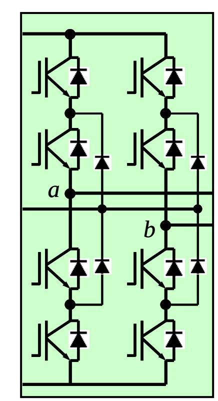


Two options to avoid high common mode voltage on upper level fuel cells

1. Add DC-DC in front of DC-AC
   - Need isolated DC-DC converter
   - Cost and complexity are nontrivial
2. Add low-frequency transformer after DC-AC
   - Low-frequency square-wave transformer is not practical unless DC-AC inverter is high-frequency PWM modulated
   - Low-frequency ripple is a problem to fuel cells



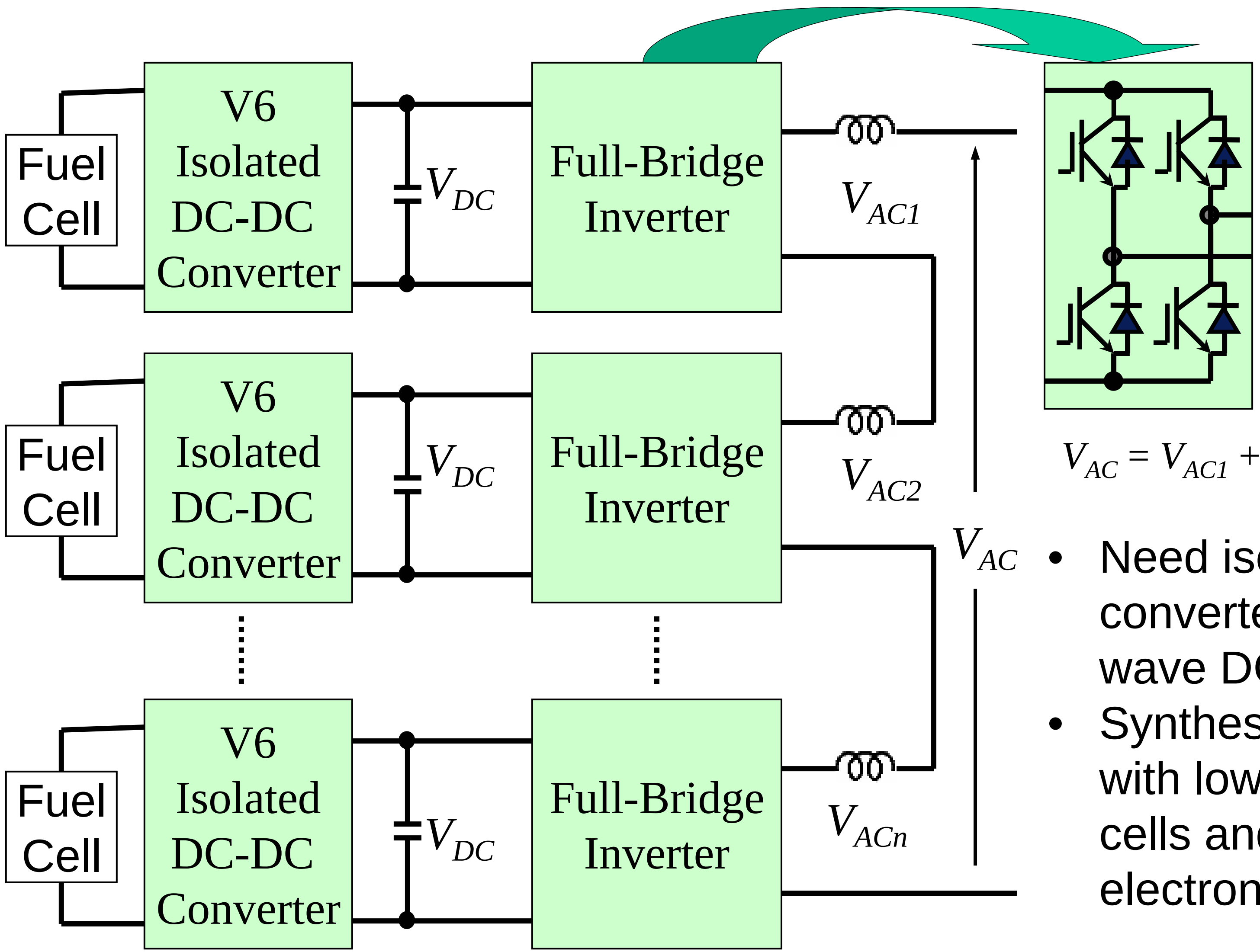
2-level



3-level

DC-AC Inverter Options

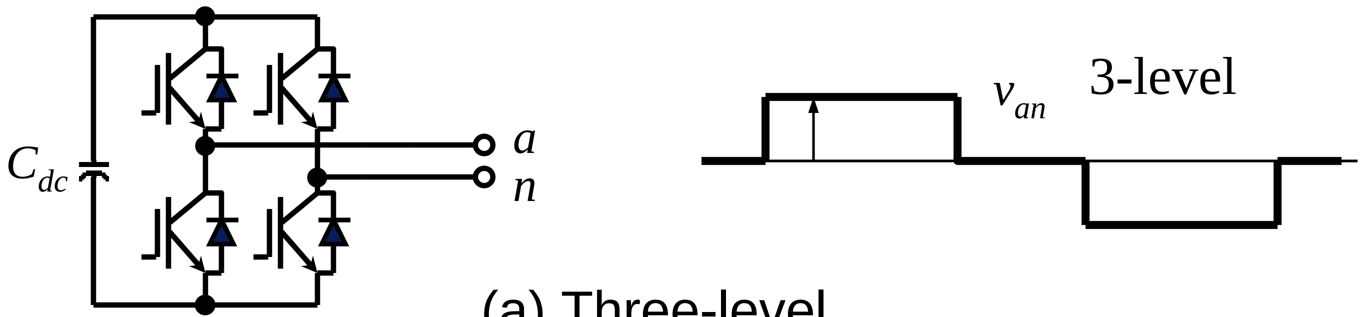
MW Power Plant Using Full-Bridge Inverters Cascaded for High-Voltage AC Systems



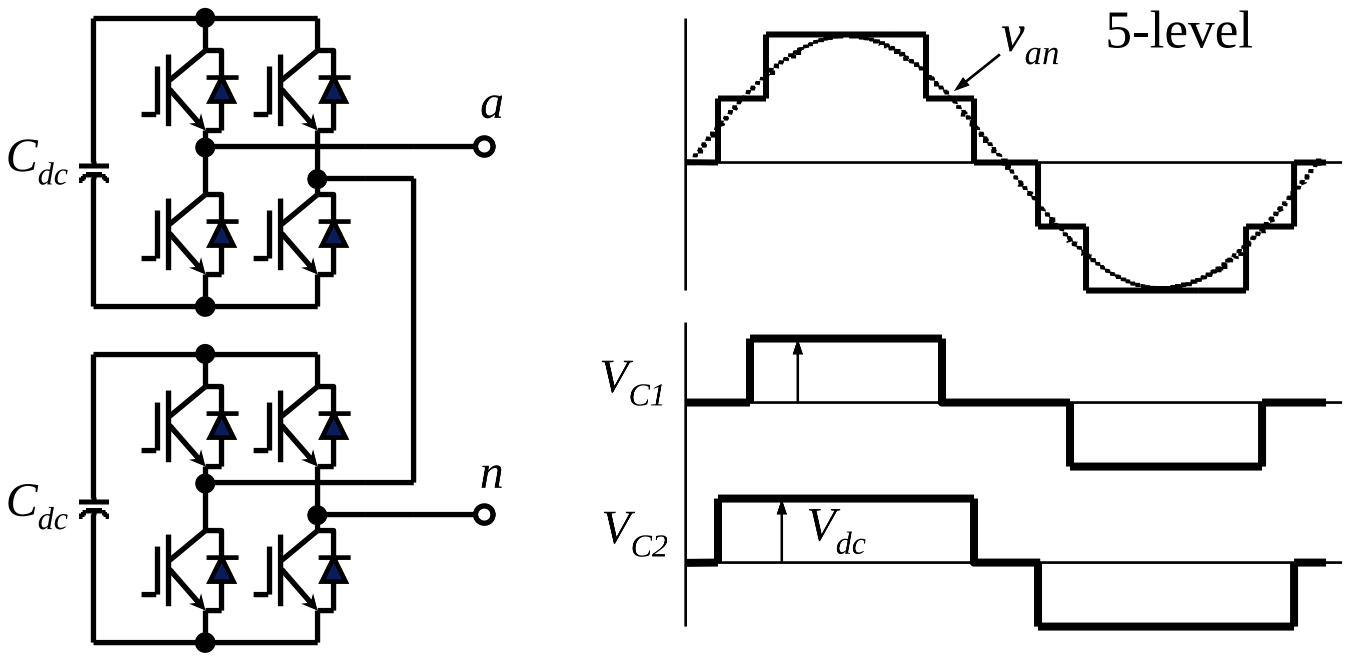
$V_{AC} = V_{AC1} + V_{AC2} \dots + V_{ACn}$

- Need isolated DC-DC converters and square-wave DC-AC inverters
- Synthesize high-voltage with low-voltage fuel cells and power electronics

Voltage Waveform of Cascaded Full-Bridge (FB) Inverters

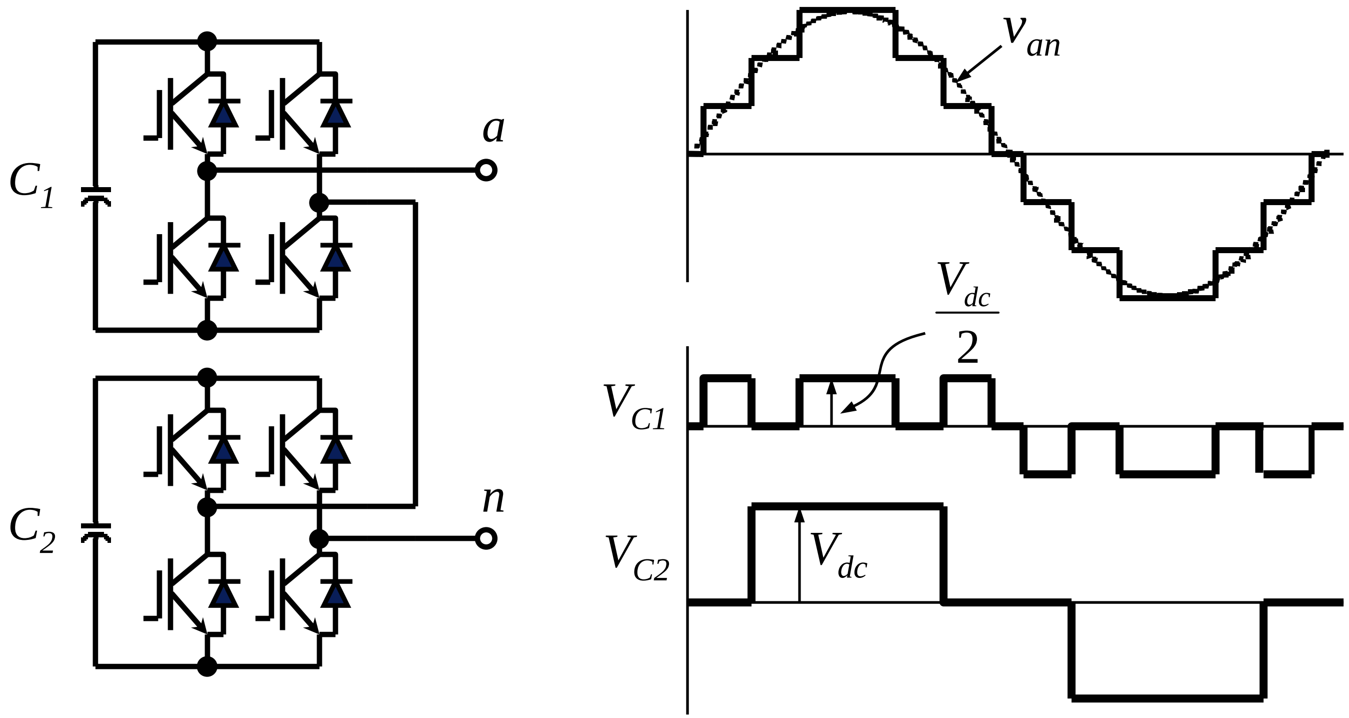


(a) Three-level



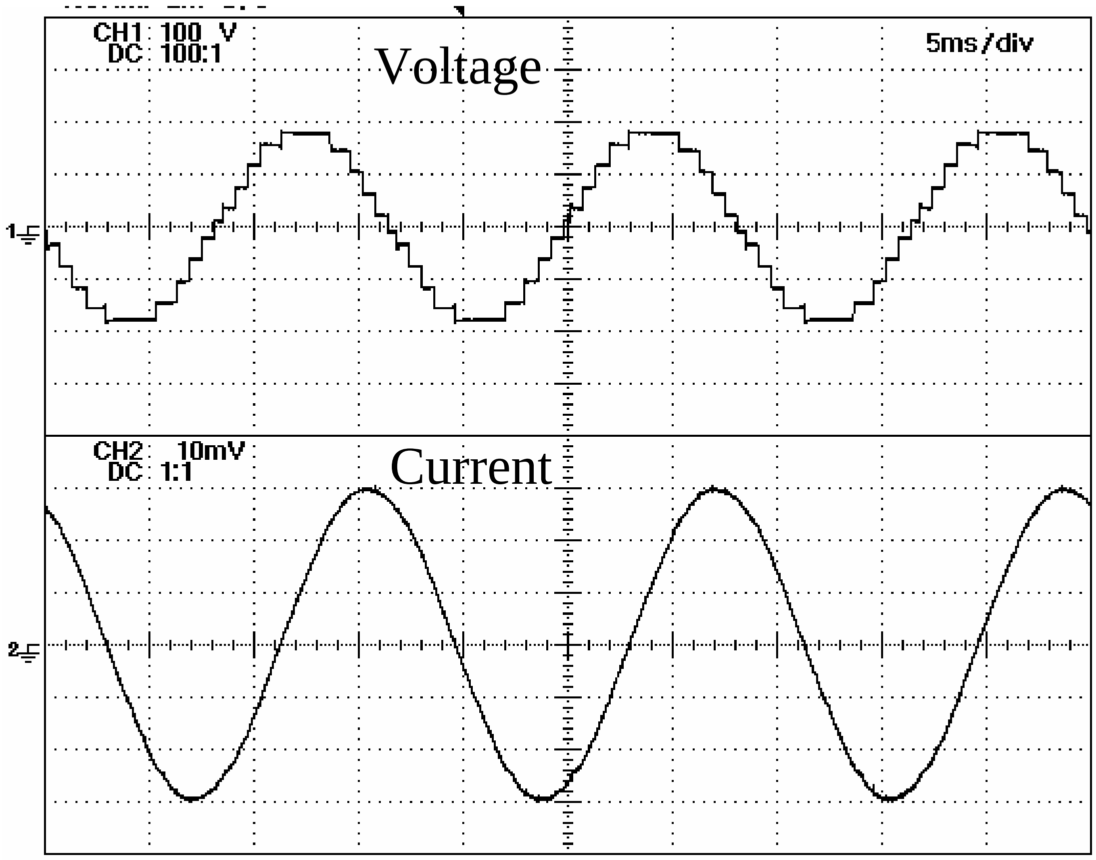
(b) Five-level

Achieving More Levels with Unequal DC Bus Voltages for Cascaded Inverter



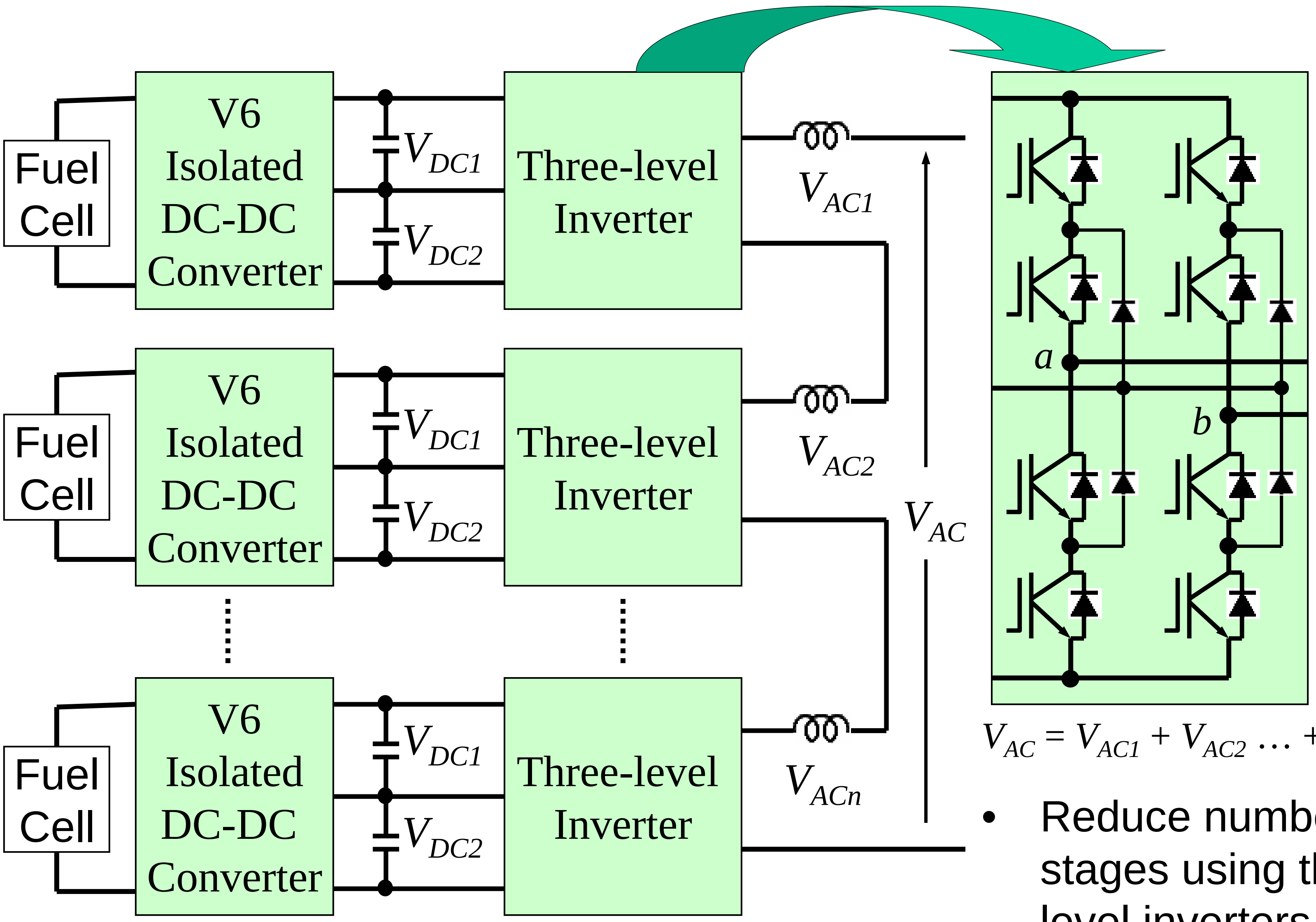
- **With unequal voltage levels, the output waveform has more ways to synthesize**
- **Two sets of cascaded inverters achieves 7-level output waveform**

Voltage and Current Waveforms of 11-Level Cascaded Inverter



- 11-level staircase voltage with cascaded inverters
- Only inductor is used as the filter to obtain clean sinusoidal current

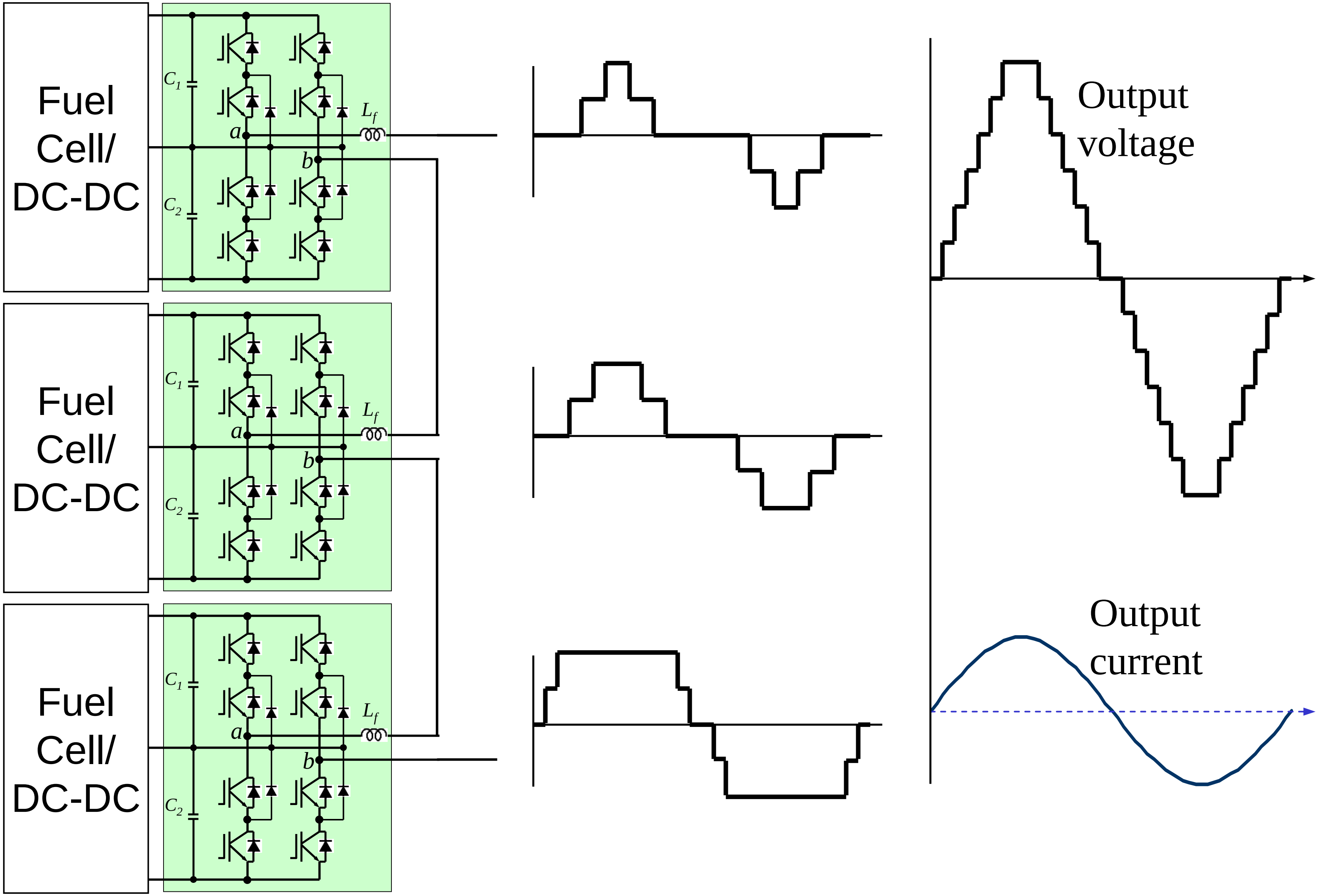
MW Power Plant Using Three-Level Inverters Cascaded for High-Voltage AC Systems



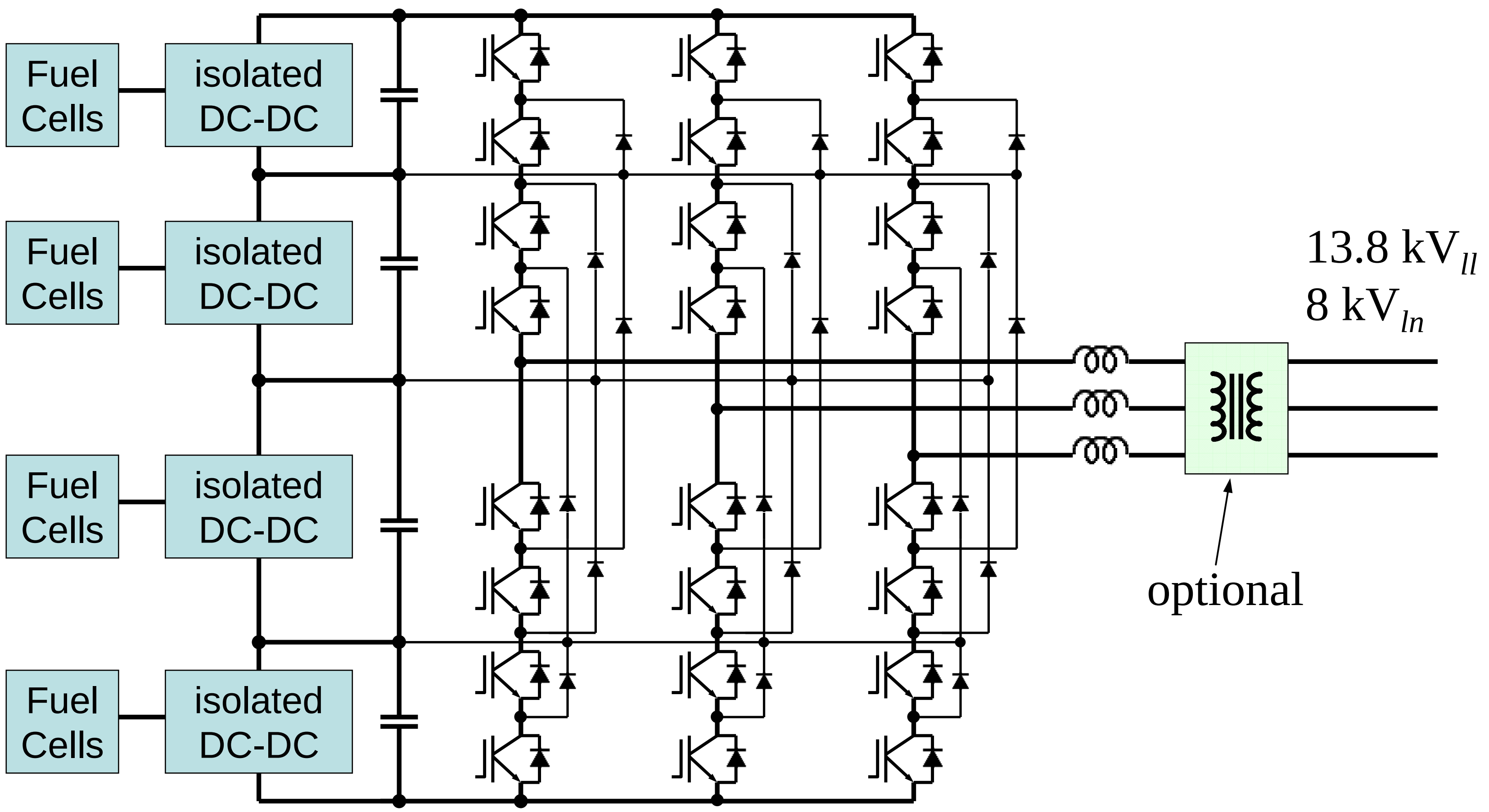
$V_{AC} = V_{AC1} + V_{AC2} \ldots + V_{ACn}$

- Reduce number of stages using three-level inverters

Cascaded Inverter with 13-Level Output



Use Fiver-Level Diode-Clamp Inverter for Possibility of Direct High Voltage Connection

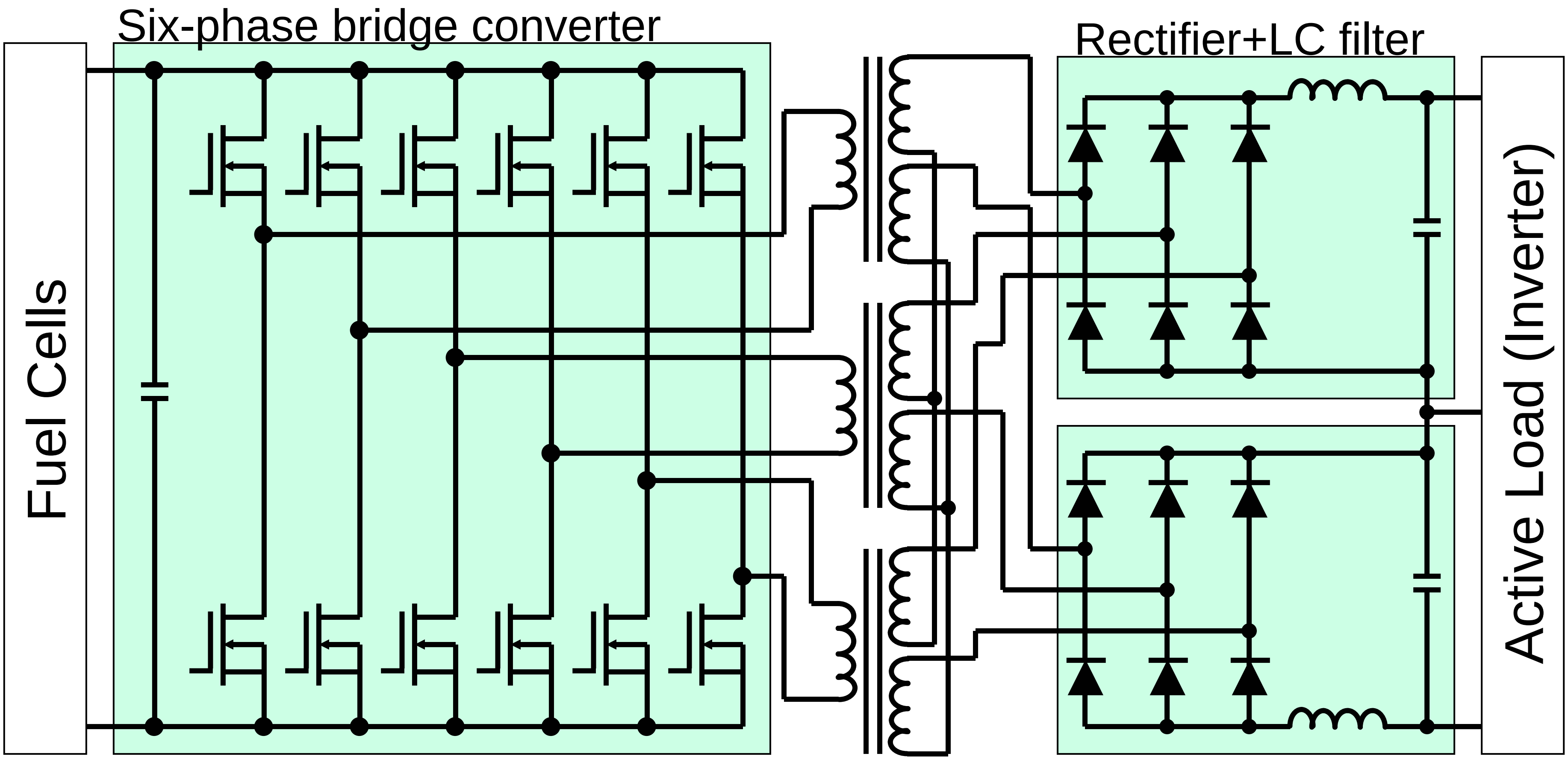


- Need isolated DC-DC to avoid CM voltage and to boost DC bus voltage
- Given 10-kV SiC device, low-frequency transformer can be eliminated
- Sensors and controls are non-trivial with 5-level inverters

DC-DC Converter is Essential for Most Topology Options

- Except for low-voltage power electronics with “fuel cell + inverter + transformer” option, all other circuit topologies need DC-DC converter for at least one of the following reasons:
  - ✓ Avoid excessive CM voltage in series fuel cell stacks
  - ✓ Isolate fuel cell output for cascaded inverters
  - ✓ Boost voltage for multilevel inverter inputs
  - ✓ Regulate voltage for inverter inputs
- Options of high-power DC-DC converters
  - ✓ Full-bridge converter
  - ✓ Multilevel converter
  - ✓ Three-phase DC-DC converter
  - ✓ V6 DC-DC converter

V6 Converter – Ideal for Fuel Cell Power Conversion

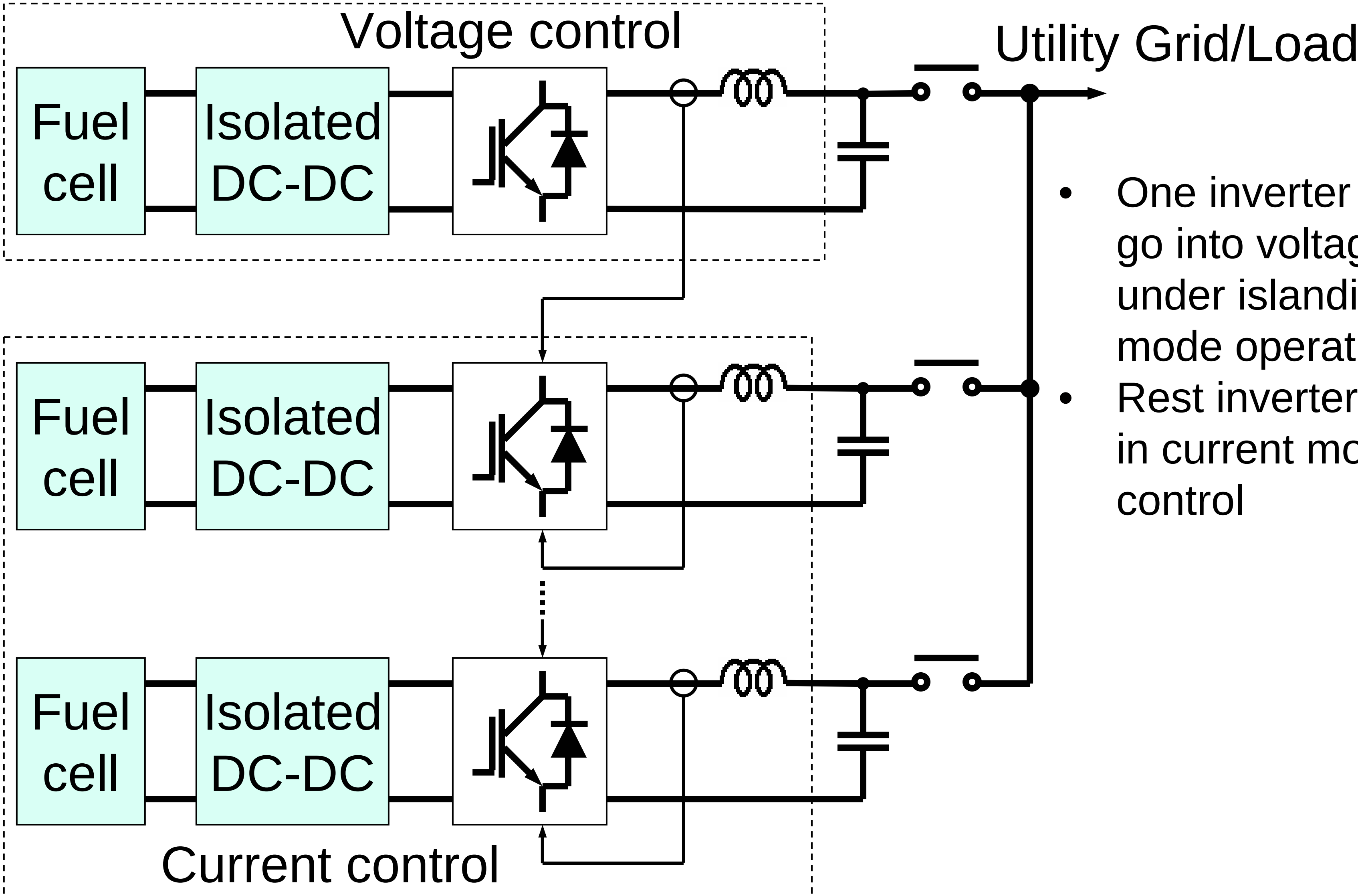


- Three full-bridge phase-shift modulated converters interleaved operation
- High-frequency ripples are cancelled ➔ minimizing filter size and loss
- Y-connected transformer secondary resets circulating current to achieve high efficiency zero-voltage zero-current (ZVZCS) switching

Options of Paralleling Fuel Cell Inverters

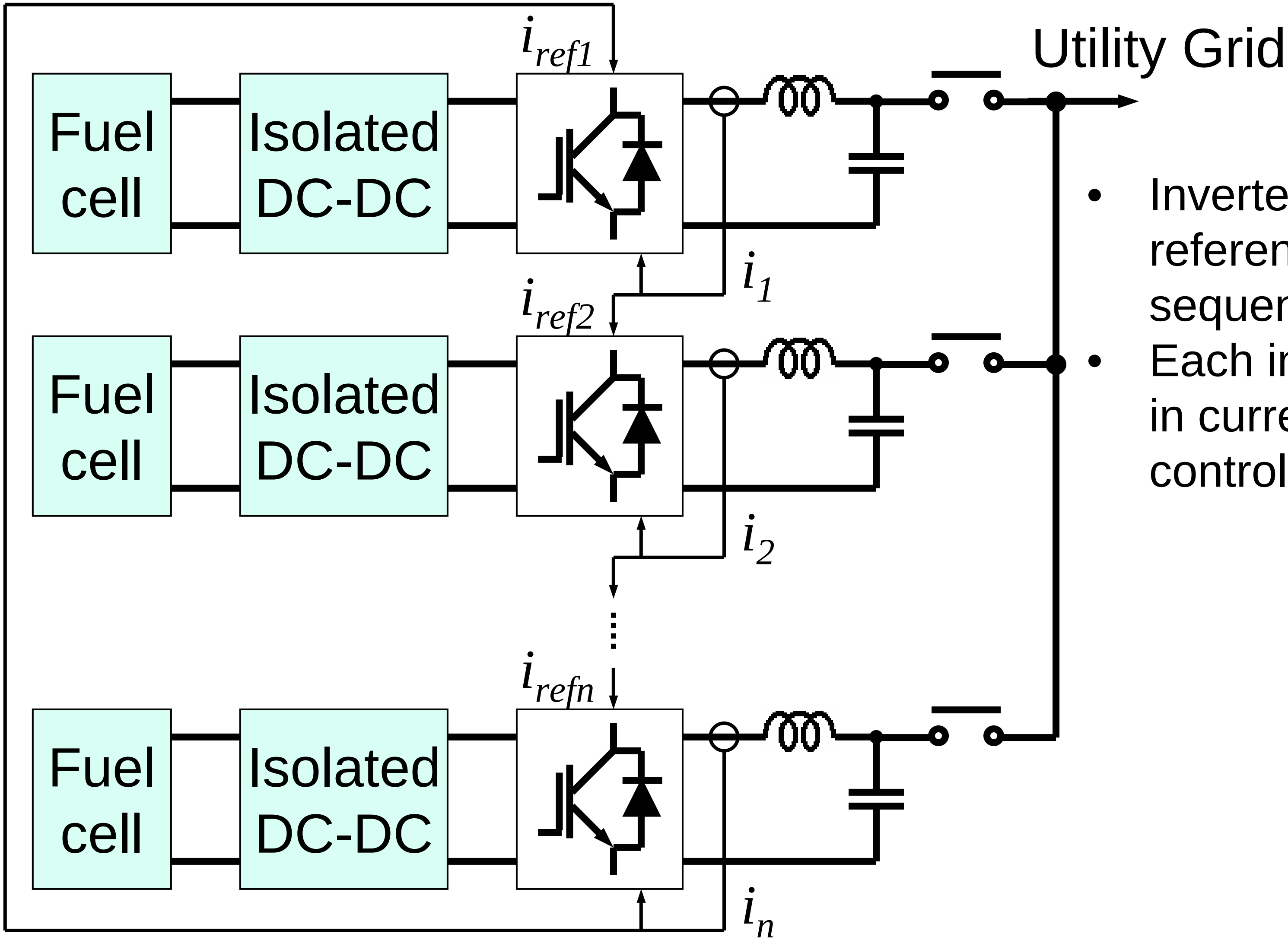
- **Mix voltage mode and current mode for universal applications that can run both grid-tie and islanding modes**
- **Circular chain current control to send current command sequentially**
- **Current distribution control with a center controller to determine current command for each inverter**

Parallel Fuel Cell Inverters with Mix of Voltage and Current Control Modes



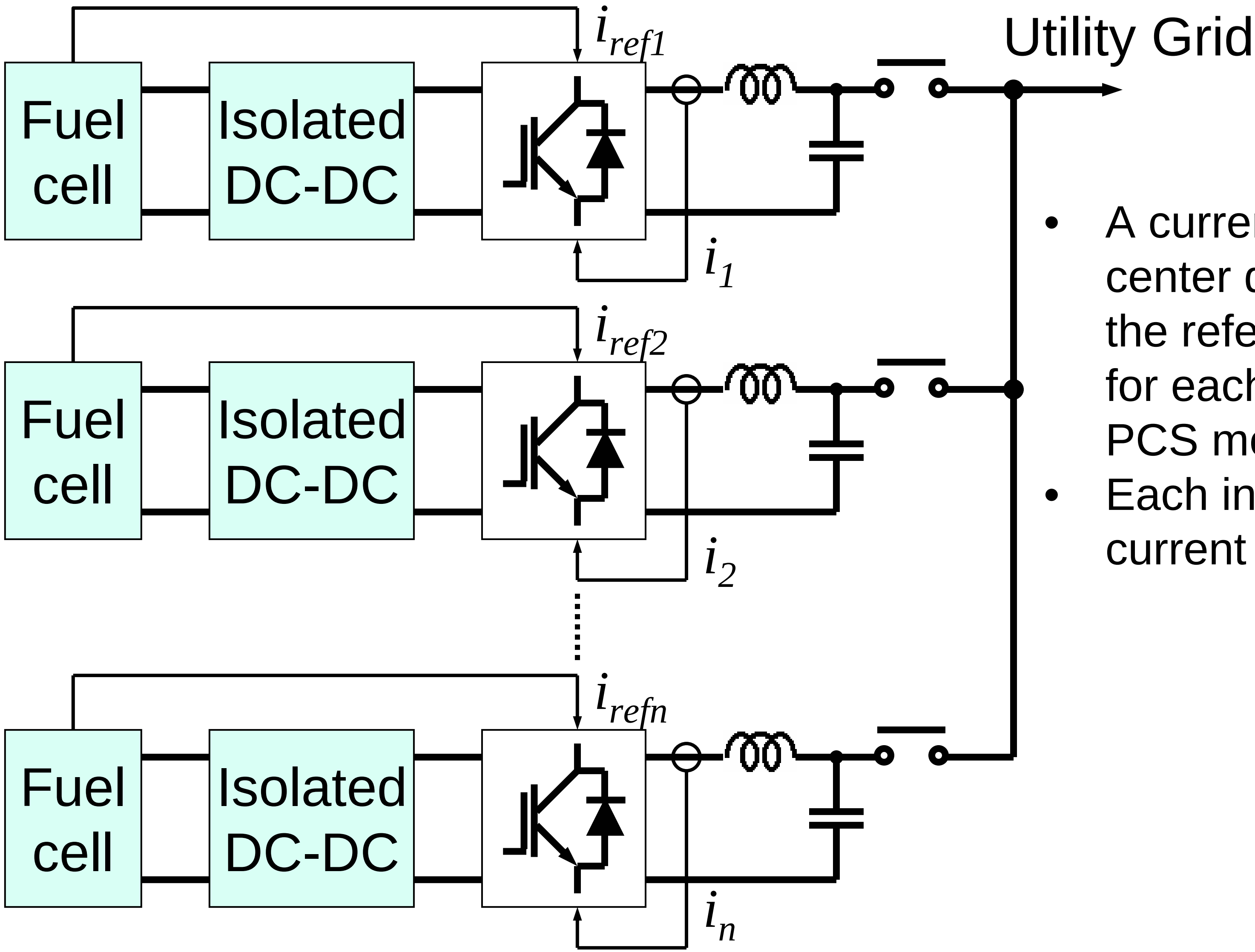
- One inverter can go into voltage under islanding mode operation
- Rest inverters run in current mode control

Parallel Fuel Cell Inverters with Circular Chain Control



- Inverter determines reference current sequentially
- Each inverter runs in current mode control

Parallel Fuel Cell Inverters with Current Distribution Control



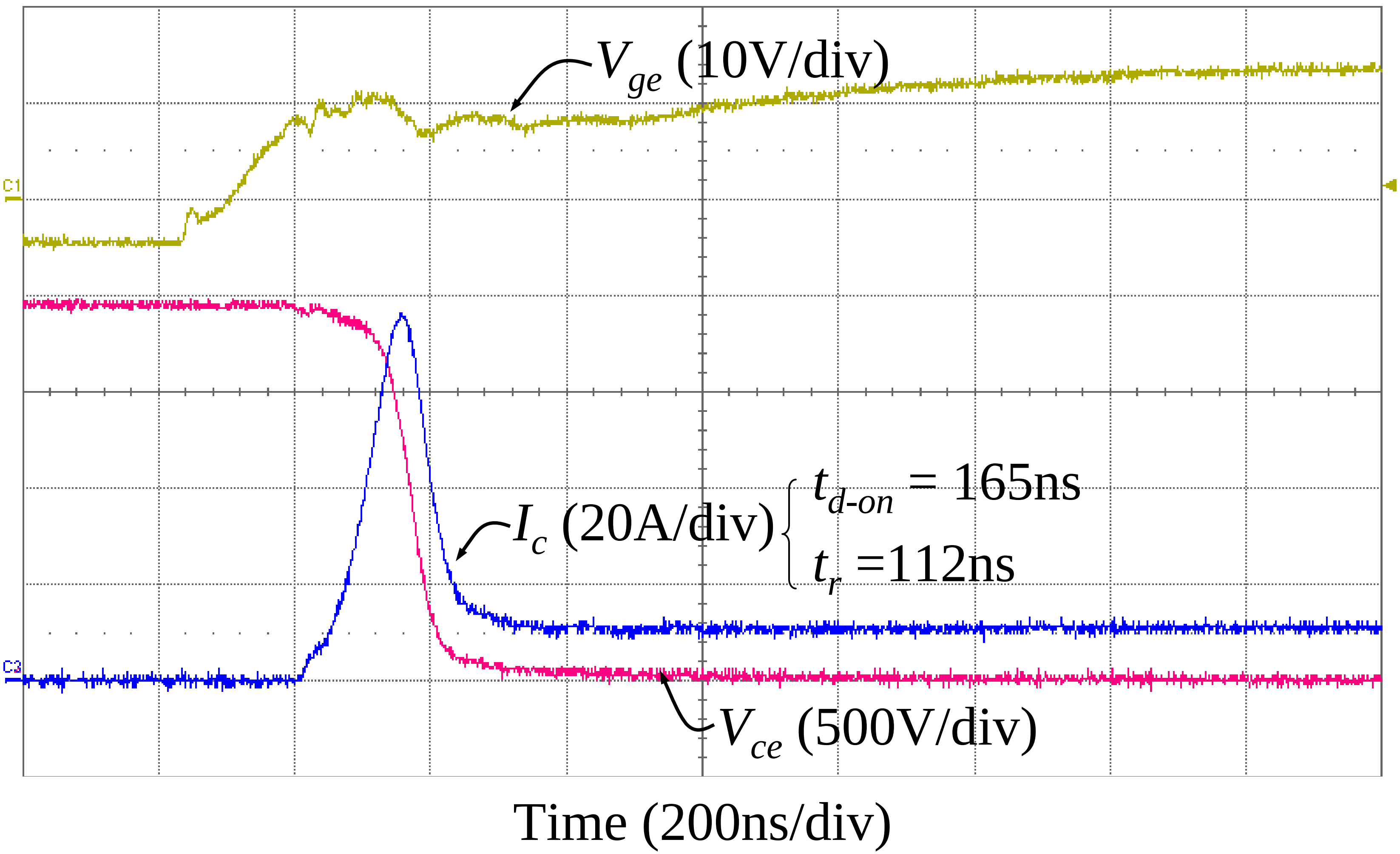
- A current distribution center determines the reference current for each fuel cell-PCS module
- Each inverter runs in current mode control

What Semiconductor Devices are Needed?

- For low-voltage power electronics options
  - ✓ 1200V-level SiC Schottky diodes to reduce the turn-on loss
  - ✓ >1kA Si IGBT
- For cascaded inverter options
  - ✓ 1200-V level SiC Schottky diodes for DC-DC converter output
  - ✓ >1kA Si IGBT
- For diode-clamp multilevel inverter options
  - ✓ 10-kV SiC device (MOSFET or IGBT)
  - ✓ 10-kV SiC diode

HV-IGBT Turn-on with Si Diode

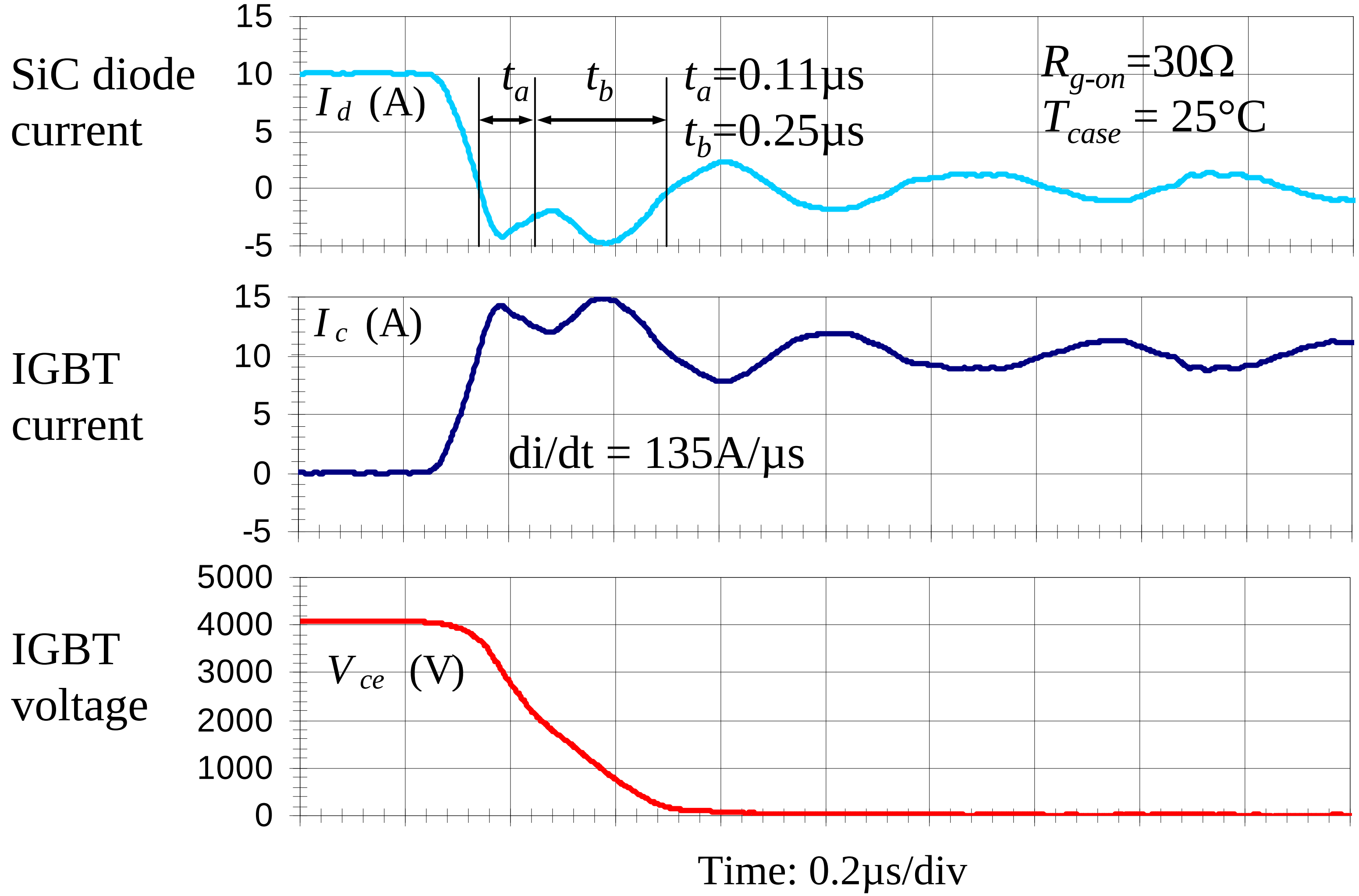
V_{dc} = 2000V, I_c = 11A, $R_{g\text{-}on}$ = 15Ω, E_{on} = 11.2mJ



HV-IGBT Turn-on with SiC Diode

V_{dc} = 4000V, I_c = 10A, $R_{g\text{-}on}$ = 15Ω, E_{on} = 3.5mJ

Significant reduction in turn-on loss even with a higher bus voltage



Summary

- **Three possible options for multi-MW fuel cell power plants**
  - ✓ **Low-voltage DC-AC inverter + low frequency transformer**
  - ✓ **Low-voltage power electronics including DC-DC and DC-AC + cascaded inverters**
  - ✓ **High-voltage power electronics including DC-DC and diode clamped multilevel inverters**
- **High-power high-efficiency DC-DC converters are needed for multilevel inverter based fuel cell power plants**
- **Multilevel inverters allow significant reduction on current ripples and their associated losses**
- **Cost reduction can be realized with passive component size reduction**
- **High-power SiC Schottky diodes are needed for most circuit configurations**

Session 4a

Ozpineci

Cascaded Multilevel Inverters for Aggregation of Fuel Cells

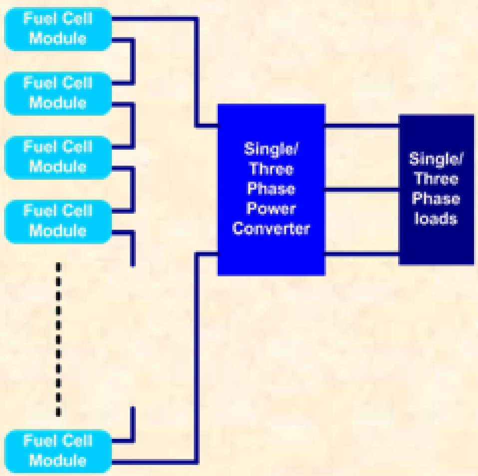
Burak Ozpineci

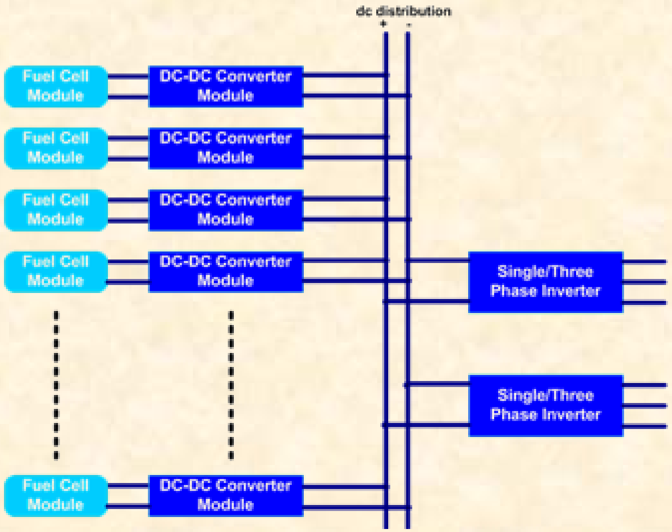
Power Electronics and Electric Machinery Research Center
Oak Ridge National Laboratory

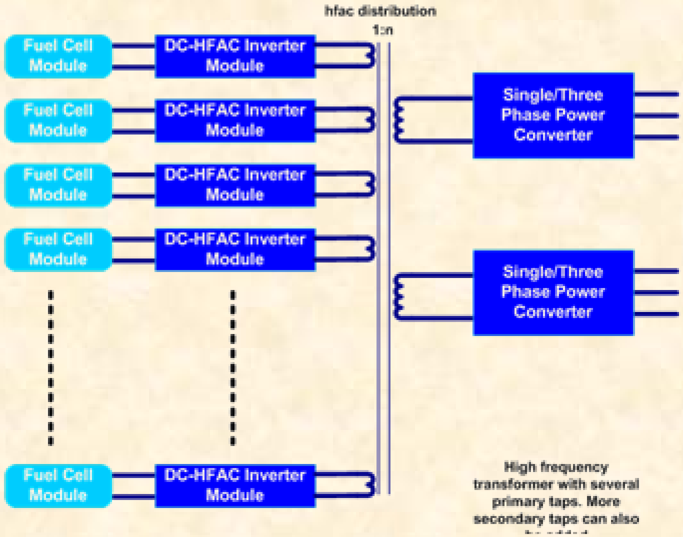
High Megawatt Converter Technology Workshop

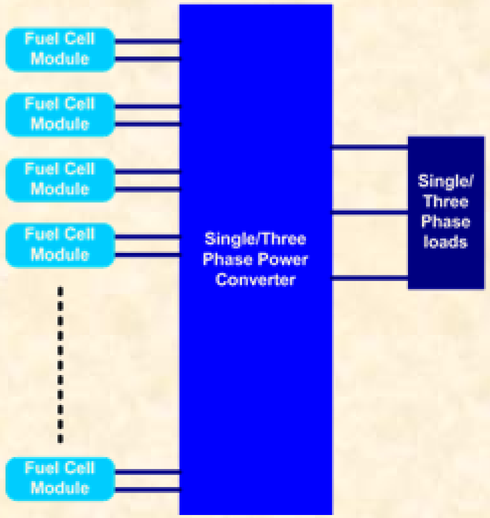
January 24, 2007

Several Possible Configurations

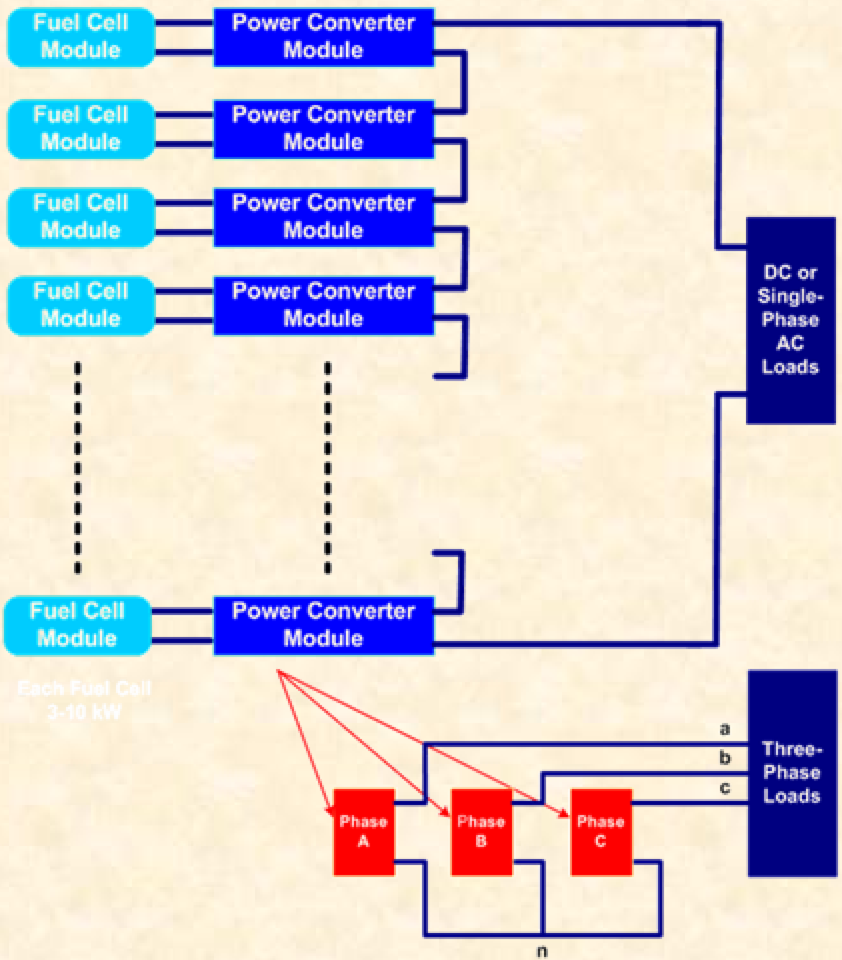








Cascade Multilevel Inverters (CMLI)



- **Each power converter module typically consists of a dc/dc voltage regulator and an H-bridge inverter**
- **Single-phase, multi-phase, three phase wye or delta connections are possible**
- **Can be used in many power applications**

Properties

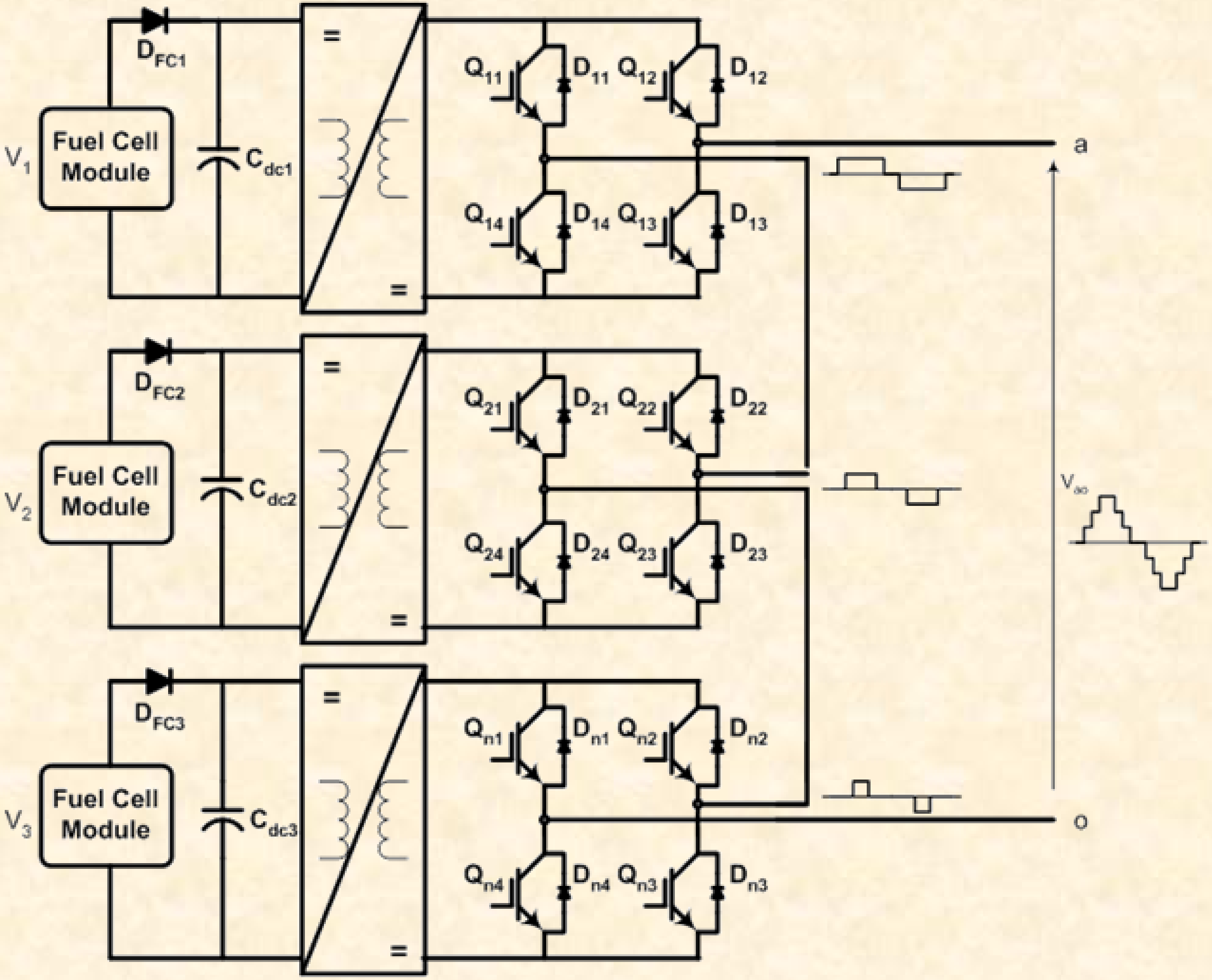
Advantages

- **Modular**
  - Reduced manufacturing and maintenance costs
- **Scalable**
  - Reduced design cost
- **Fault tolerant operation**
  - Increased availability
  - Redundant levels
  - Possible reconfiguration
- **Energy storage**
- **Low harmonic distortion**
  - Reduced filters

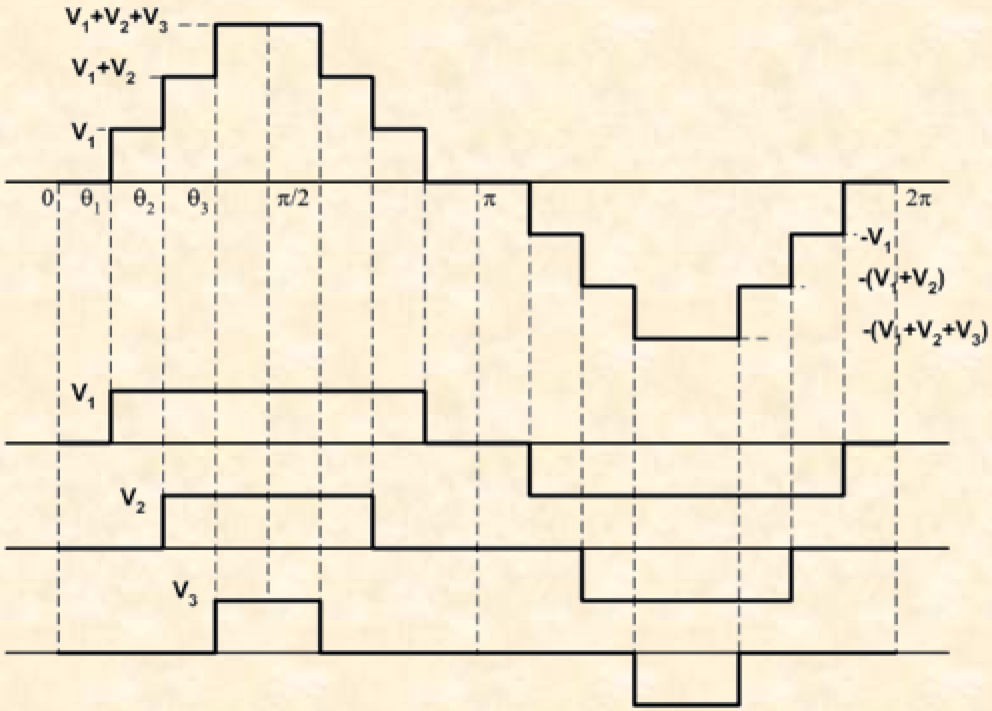
Disadvantages

- **Component count**
  - Extra switches and transformers
  - Higher component cost
  - Low voltage components
- **More complicated control**
- **Isolated dc sources**

Circuit Diagram

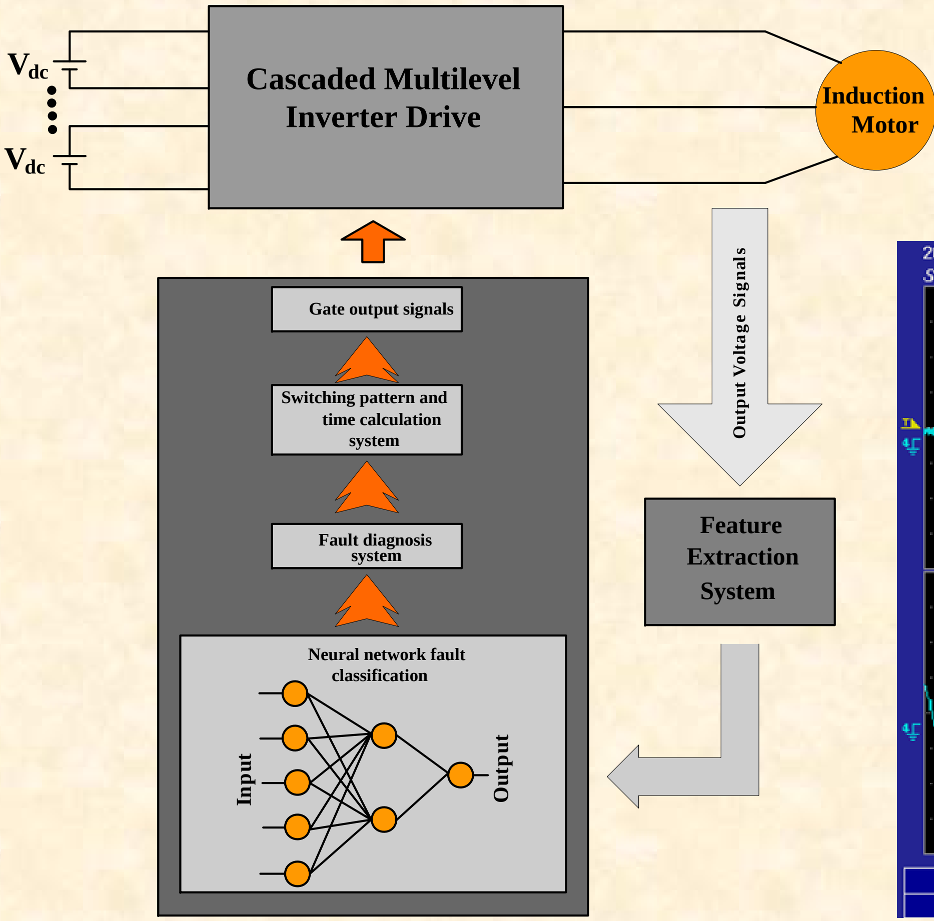


Waveform Generation

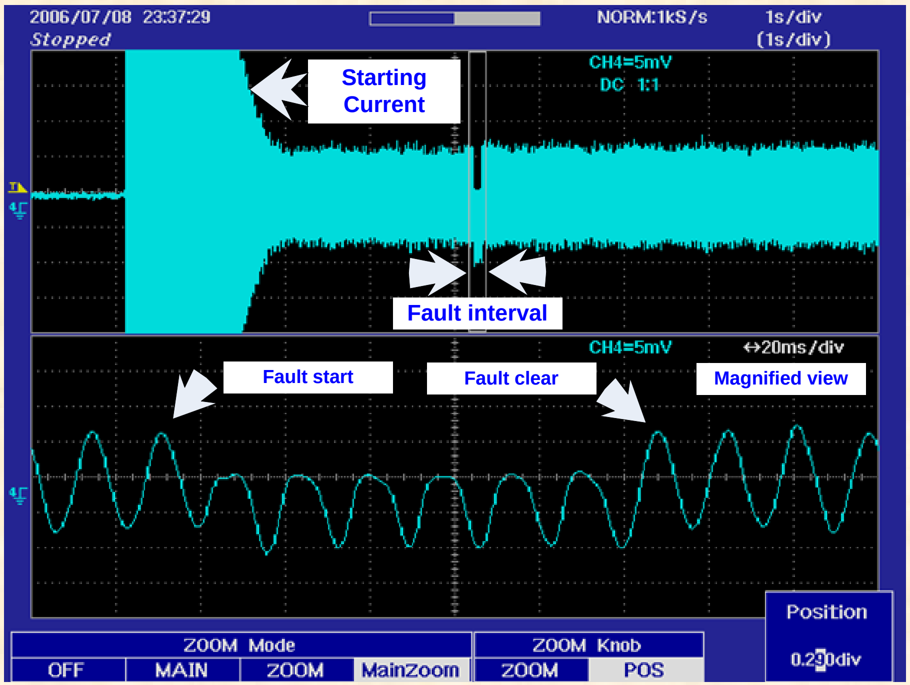


- Synthesize desired ac voltage from several levels of dc voltages
- More levels produce a staircase waveform that approaches a sinusoid
- Harmonic distortion of output waveform decreases with more levels
- No voltage sharing problems with series connected devices
- Low dV/dt reduces switching losses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

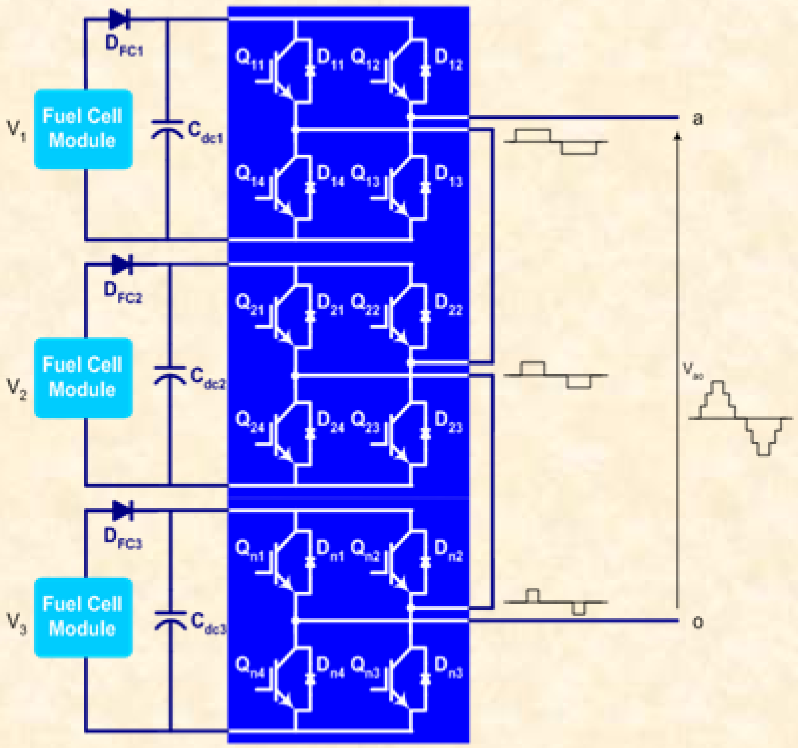
Fault Tolerant Operation



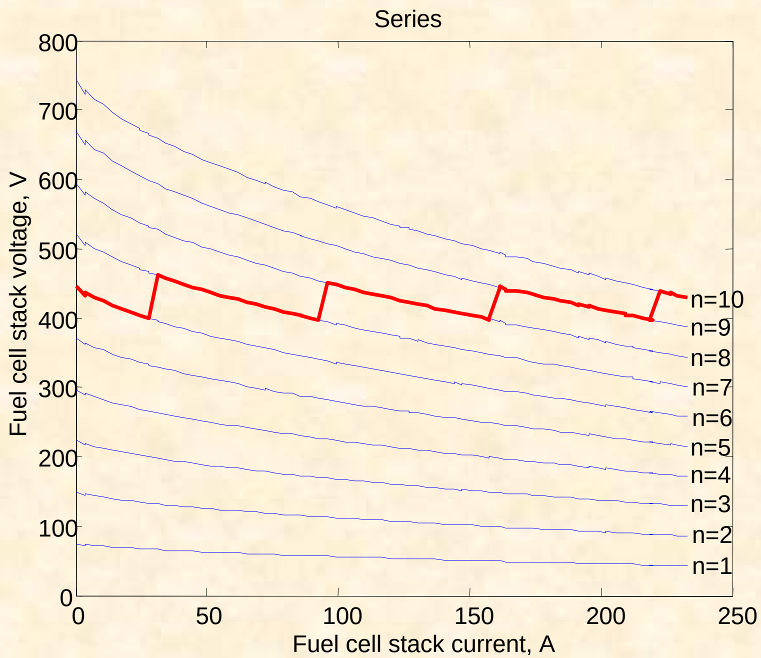
Open circuit fault



Alternative CMLI

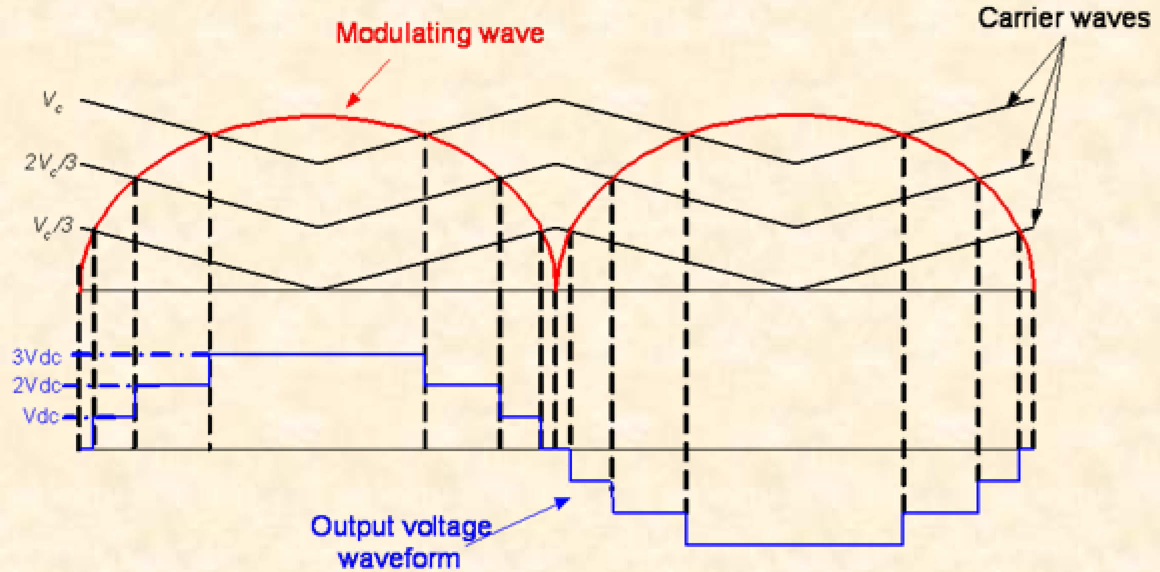


7-level cascaded multilevel inverter



Level reduction technique for a 10 dc source CMLI

Multilevel Modulation at Fundamental Frequency



V_{ao}^*: modulating wave

V_c : carrier wave

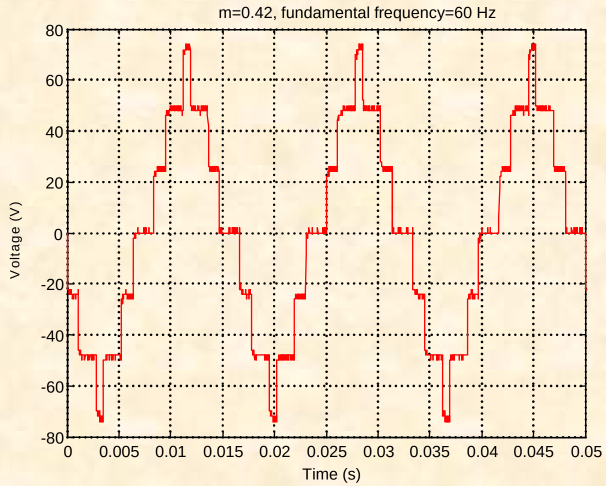
$2V_c/3 < V_{ao}^*$: 7-levels

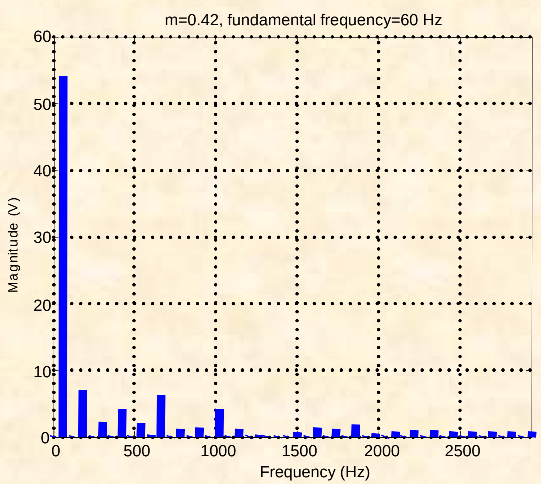
$V_c/3 < V_{ao}^* < 2V_c/3$: 5-levels

$0 < V_{ao}^* < V_c/3$: 3-levels

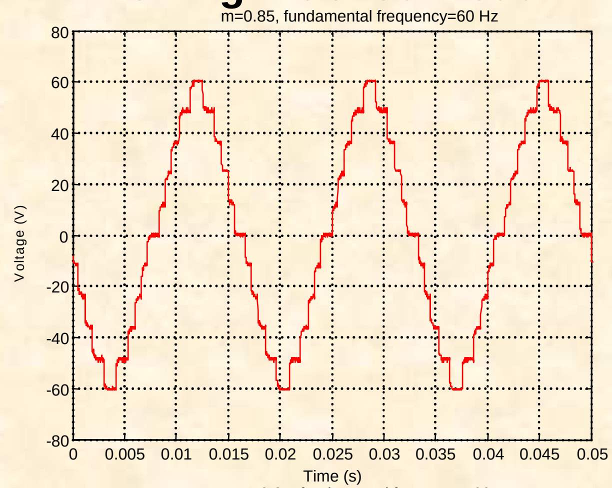
Output Voltage Waveforms

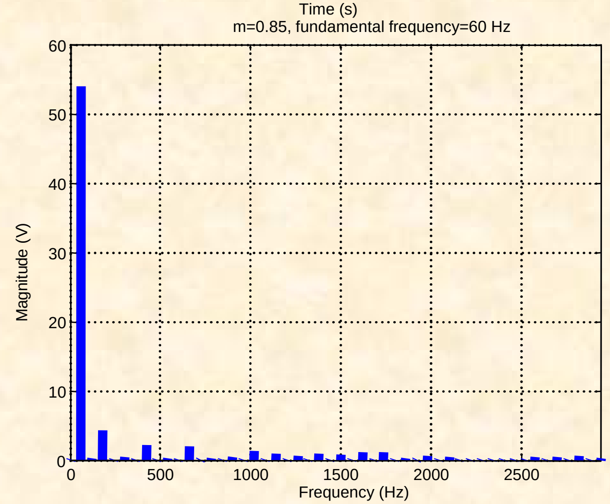
7-level output voltage waveform for low fuel cell load





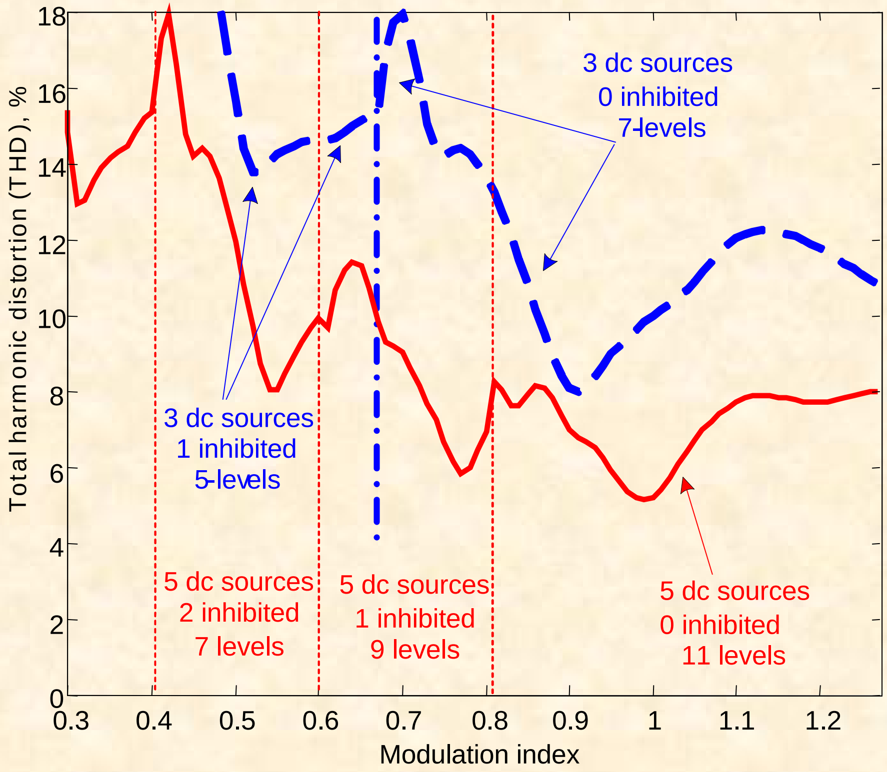
11-level output voltage waveform for high fuel cell load





Same peak fundamental voltage

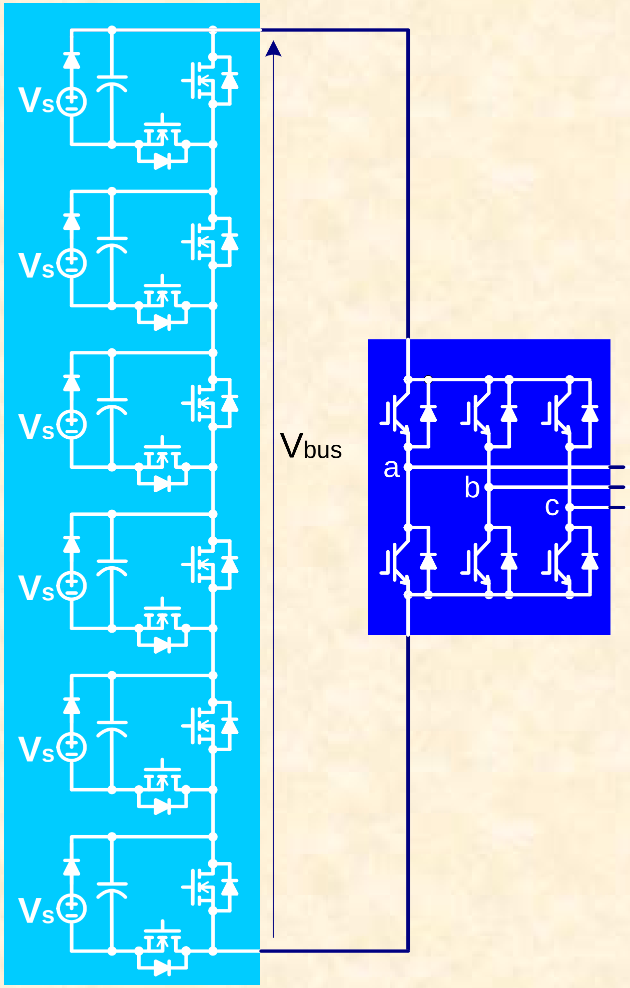
Total Harmonic Distortion



Total harmonic distortion of the output voltage with respect to the modulation index (up to 41st harmonic)

- **No filtering**
- **For lower total harmonic distortion**
  - **Multilevel PWM**
  - **Optimized switching angles**

Another Alternative CMLI



- **Vertical switch (S_{v1}) OFF**

  Horizontal switch (S_{v1}) ON

  ⇒Fuel cell supplies power

- **Vertical switch (S_{v1}) ON**

  Horizontal switch (S_{v1}) OFF

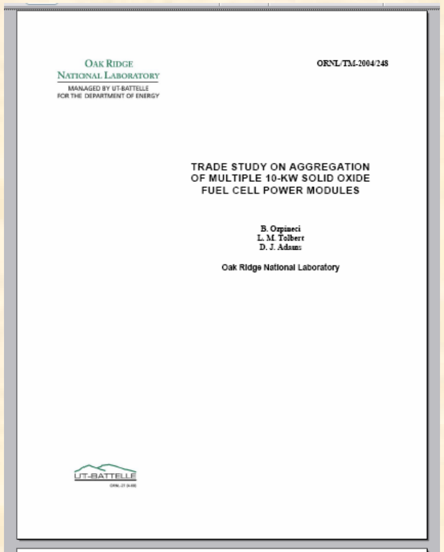
  ⇒Fuel cell inhibited

For More Information

http://www.ornl.gov/peemrc/
http://www.ntrc.gov/

http://www.ornl.gov/~webworks/cppr/y2001/rpt/121814.pdf

TRADE STUDY ON AGGREGATION OF MULTIPLE 10-KW SOLID OXIDE FUEL CELL POWER MODULES



Session 4b

Grider

Recent Developments in SiC Power Technology at Cree

High Megawatt Converter Technology Workshop

January 24, 2007

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

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SiC Power Devices

- SiC Material Advantages for Power
- 1200 V JBS Diodes
- 1200 V SiC DMOSFETs
- SiC Device Scaleup & Yield Improvement
- 10 kV SiC DMOSFETs
- SiC PiN Diodes, p-IGBTs, and Thyristors

SiC Materials Advantages For Power Device Technology

10X Breakdown Field of Si

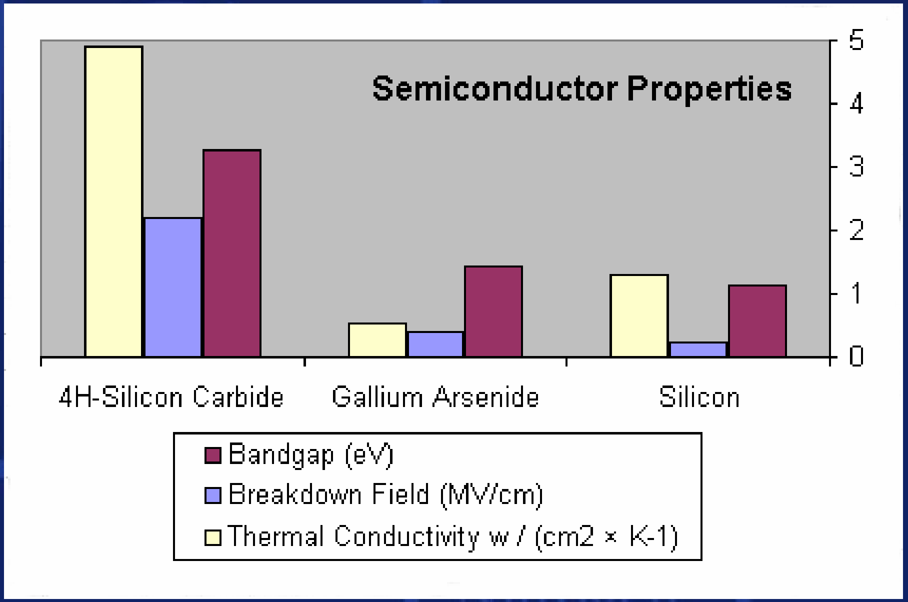
- Tradeoff higher breakdown voltage
- Lower specific on-resistance
- Faster switching

3X Thermal Conductivity of Si

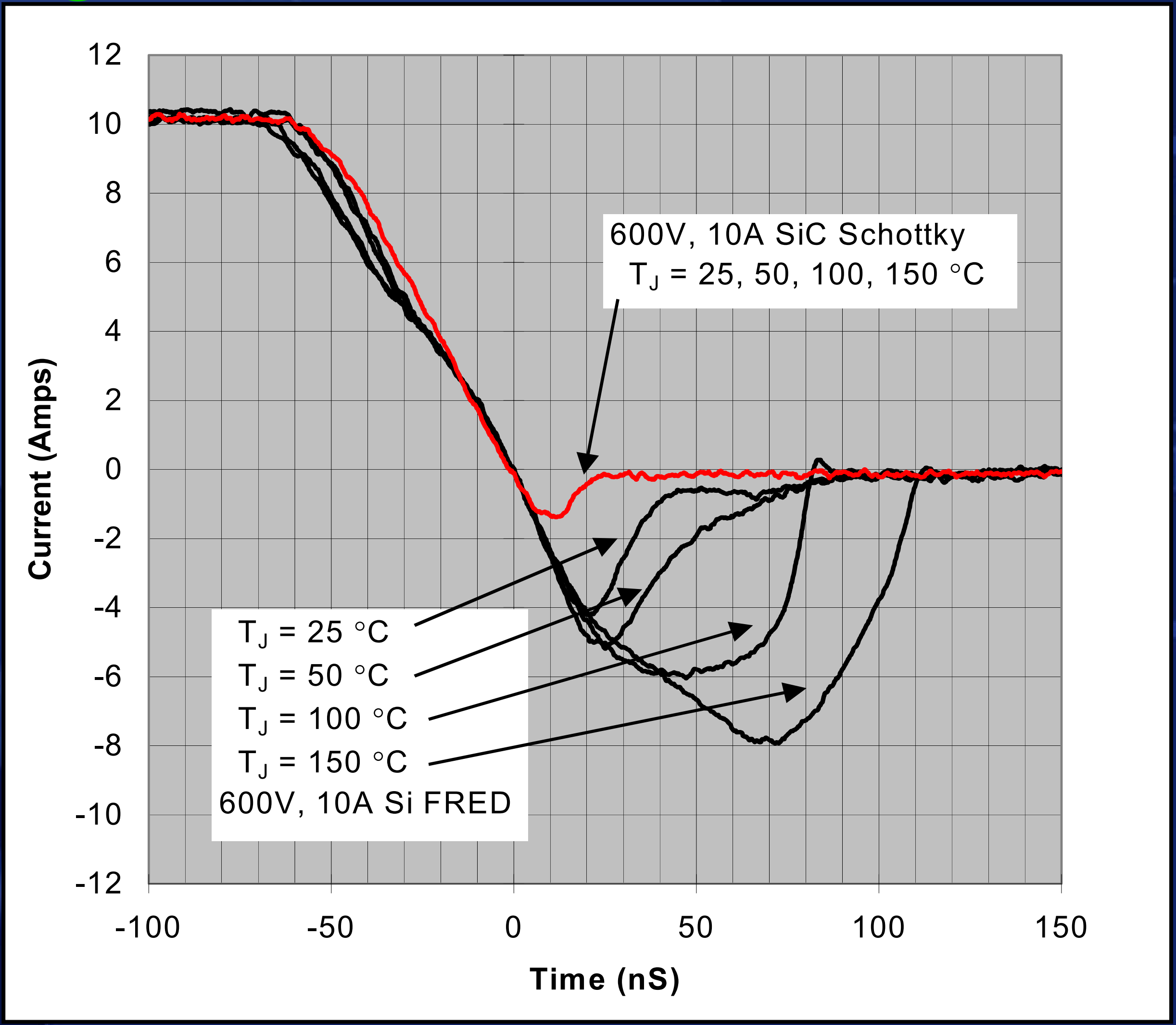
- Higher current densities

3X Bandgap of Si

- Higher temperature operation



600 volt SiC Schottky and Si PiN Diode Reverse Recovery Comparison

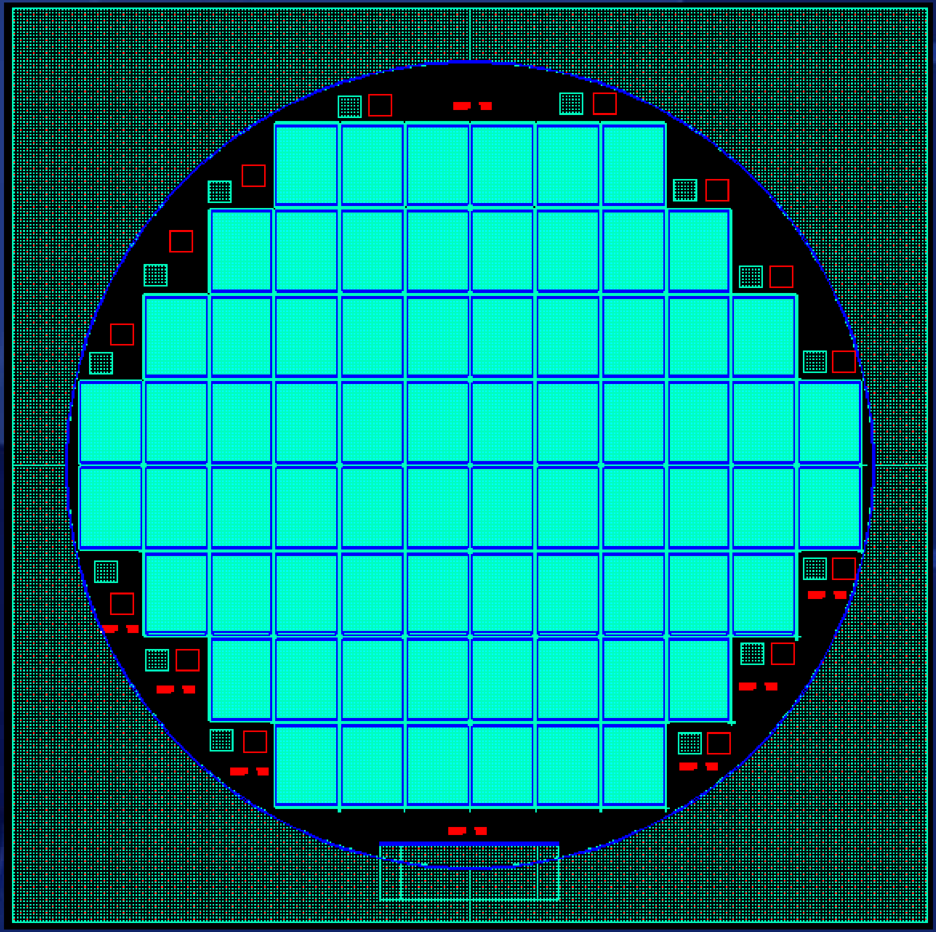


- **Si PiN Diode**
  Reverse recovery increases with temperature, slew rate and forward current

- **SiC Schottky**
  Virtually no reverse recovery, regardless of temperature, slew rate,

1200 V 75 A JBS diodes

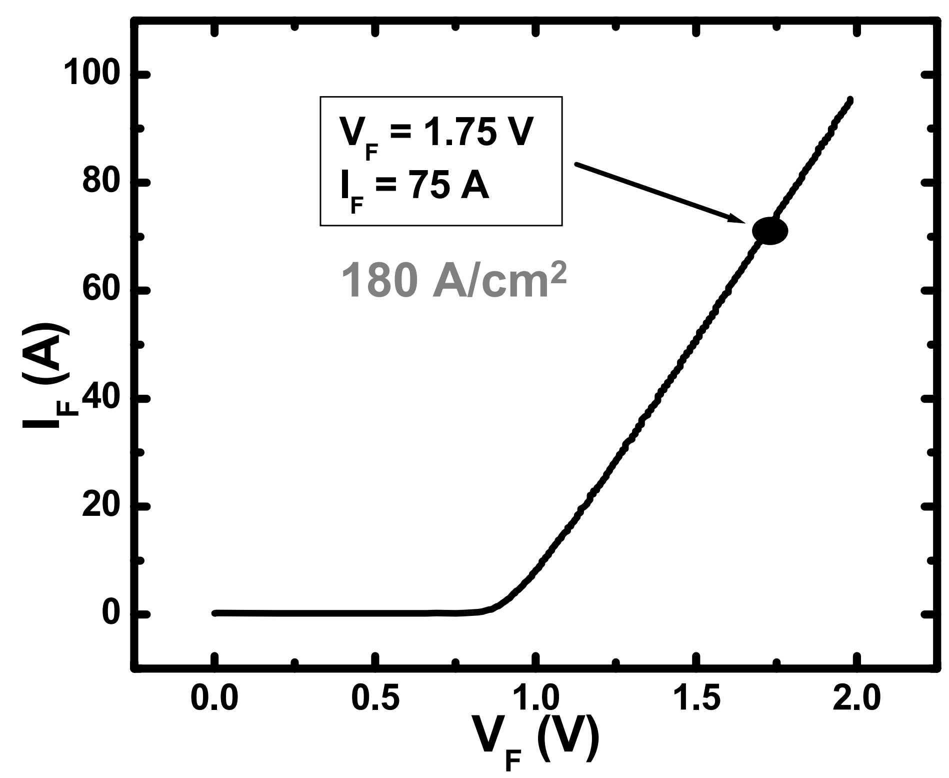
1200 V / 75 A

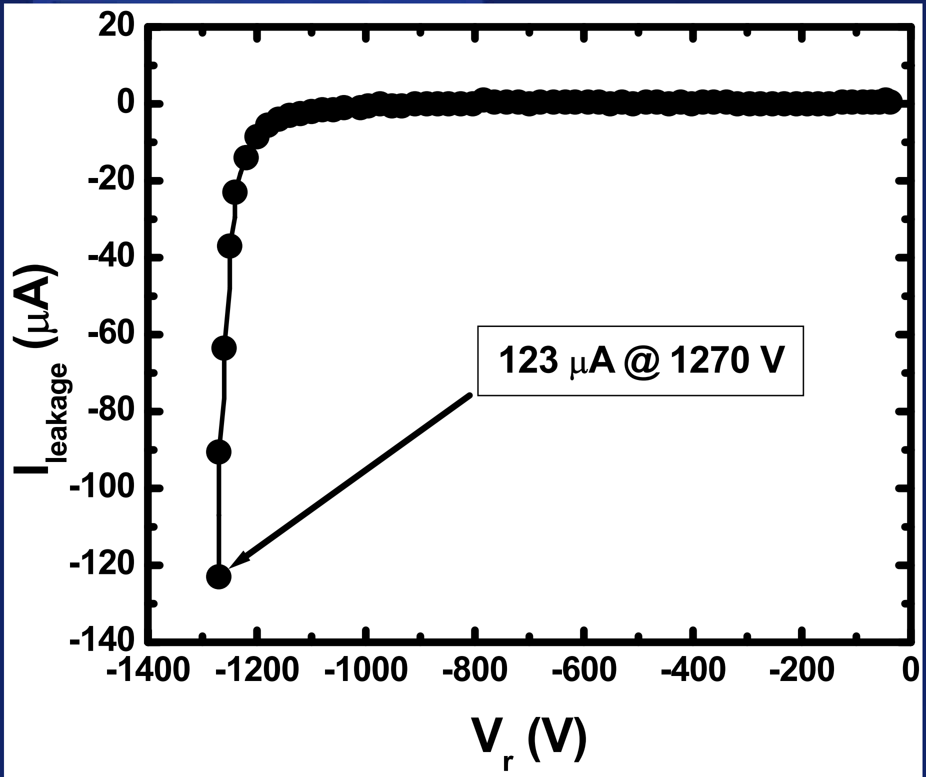


Die size: 6 mm x 8 mm

Active area: 0.413 cm^2

1200 V / 75A diode I-V Characteristics





A SiC Switch Is Required For Even More Efficiency Improvement

SiC Power Switches Currently Being pursued:

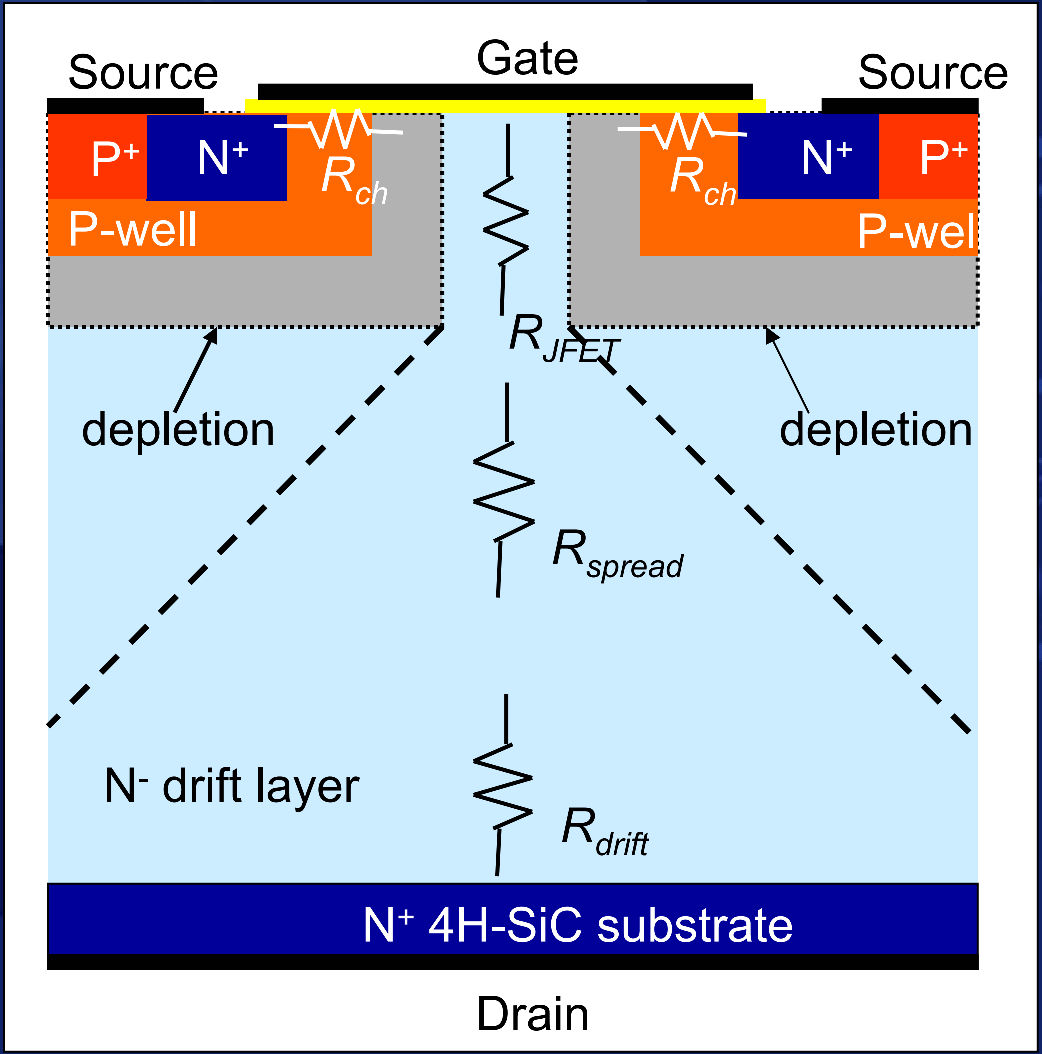
- DIMOSFETs
- UMOSFETs
- Vertical JFETs
- IGBTs
- BJTs
- Thyristors/GTOs

Increasing Voltage ↓

Decreasing Speed ↓

Increasing Operating Temp ↓

Double Implanted MOSFET (DMOSFET)



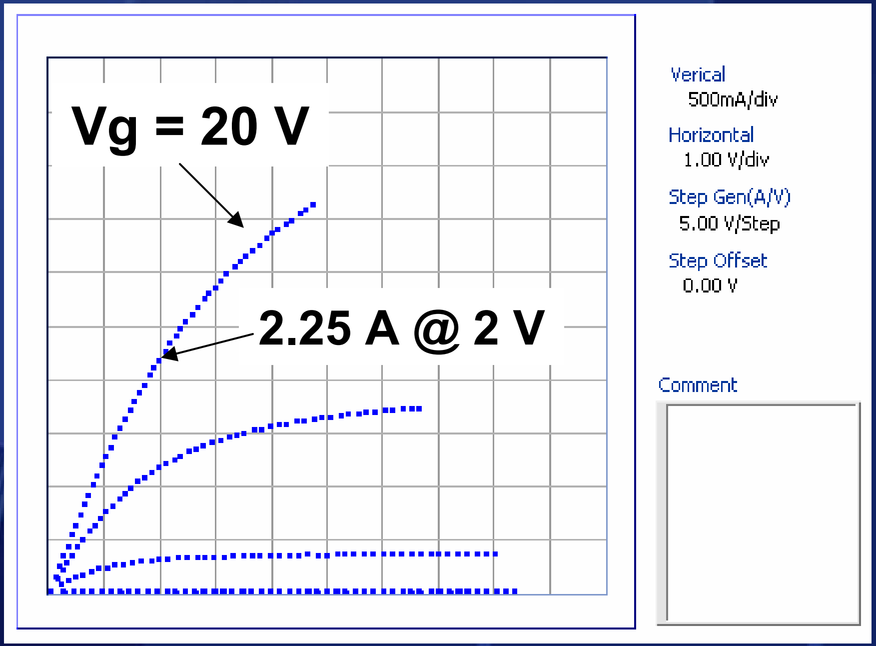
Pursuing DMOSFET As Switch From 600V Up To 10kV

DMOSFET Requirements

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

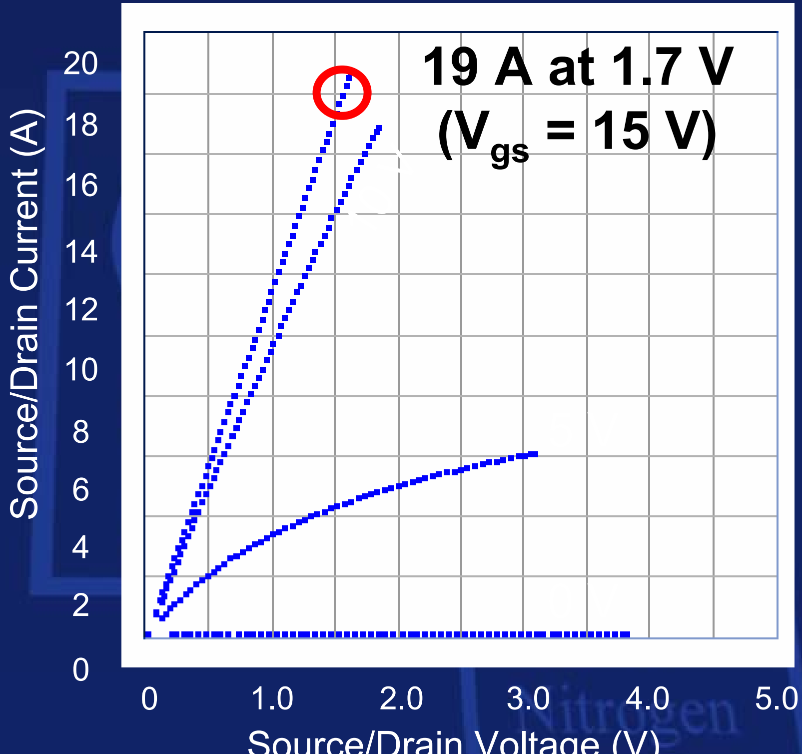
Dramatic Reduction in 25 ºC 1.2 kV DMOSFET On-Resistance

January 2004



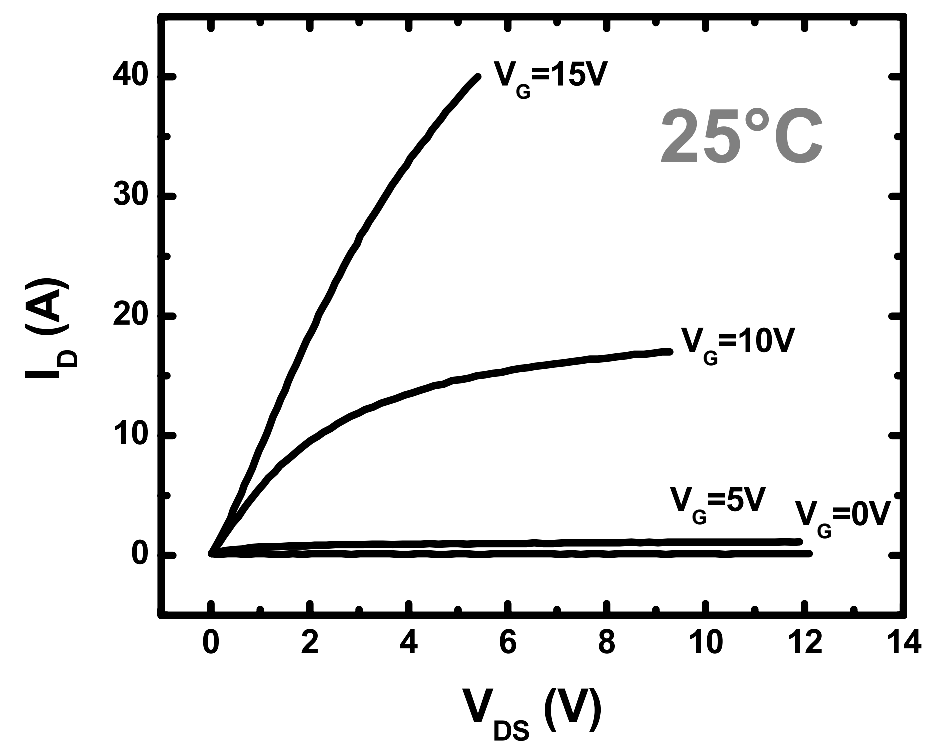
21.8 mΩ-cm²

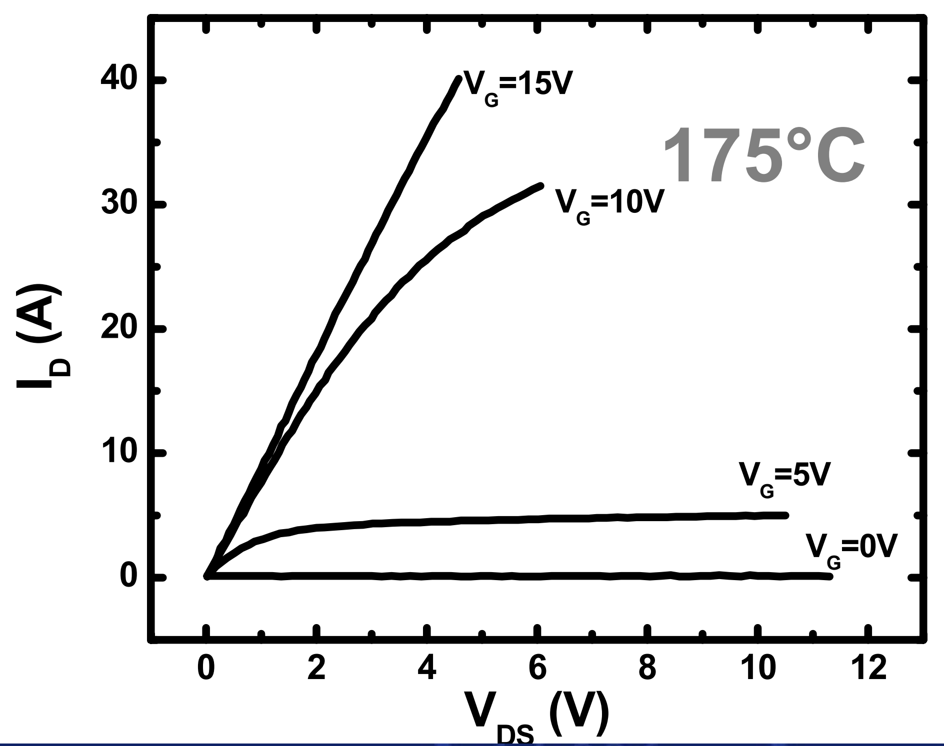
March 2006



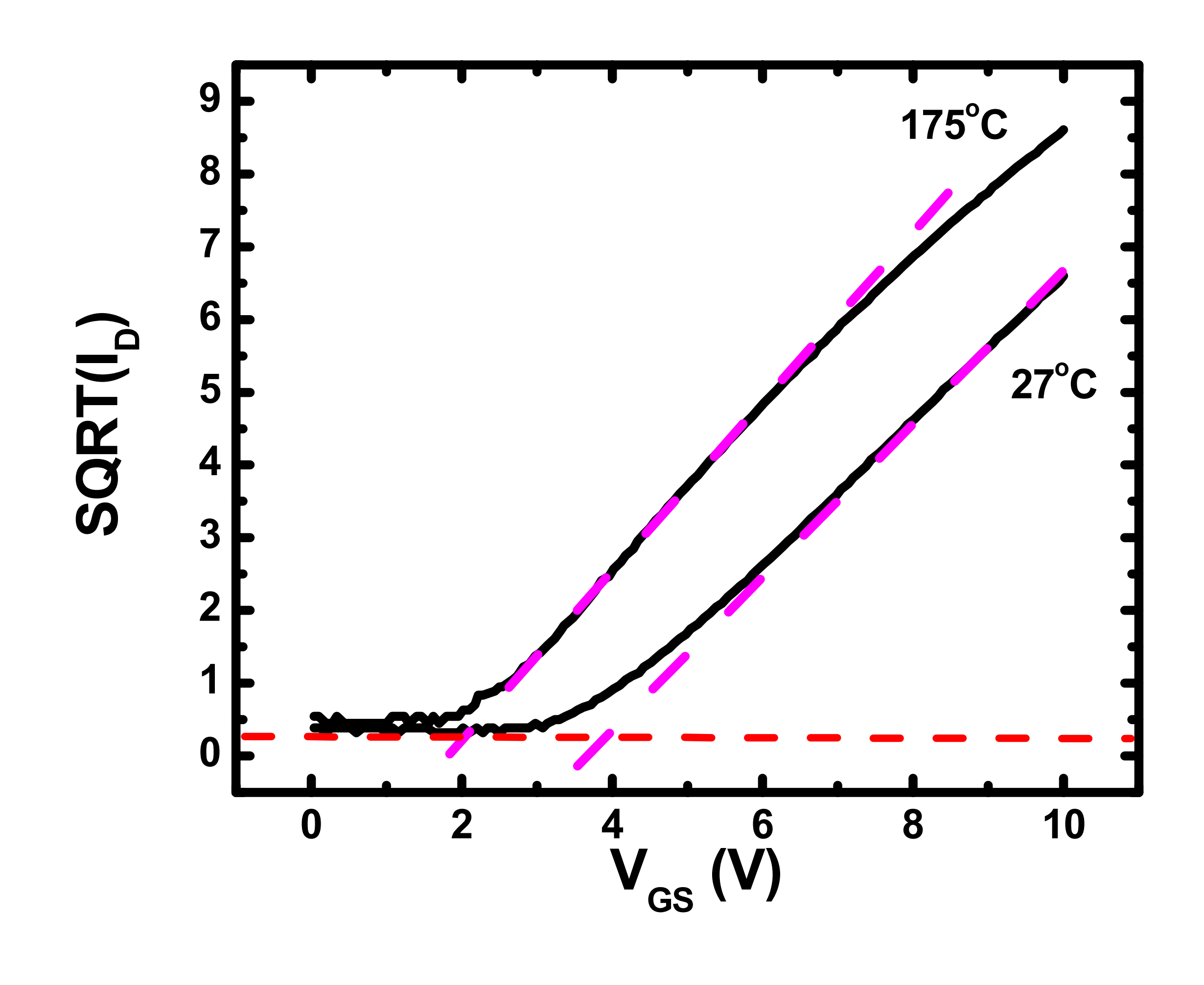
8.1 mΩ-cm²

1200 V/15 A SiC Power MOSFET – DC Data

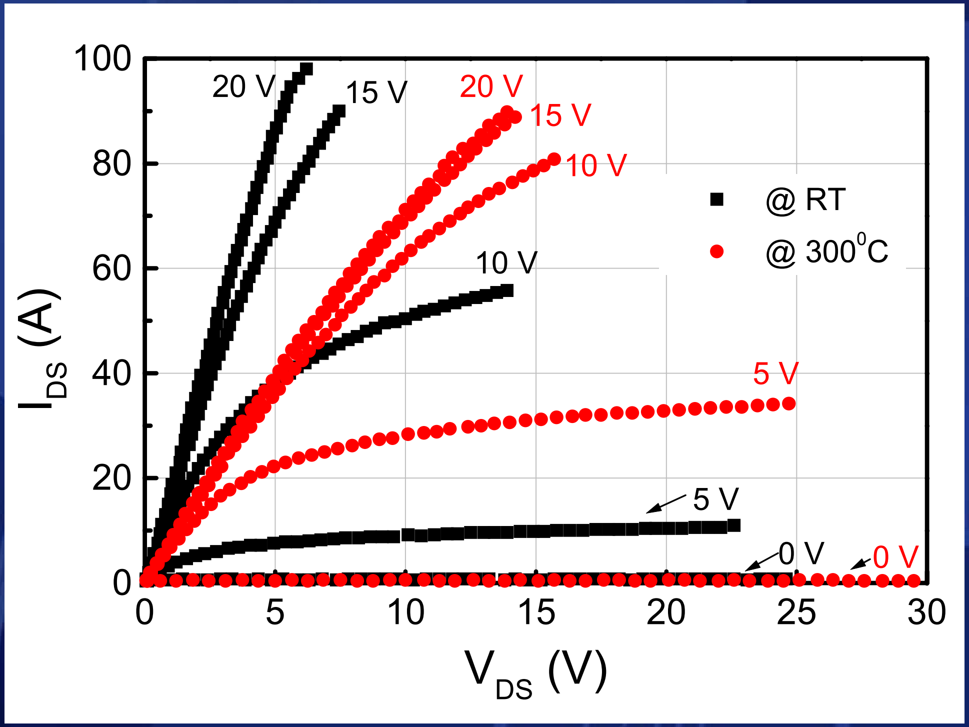


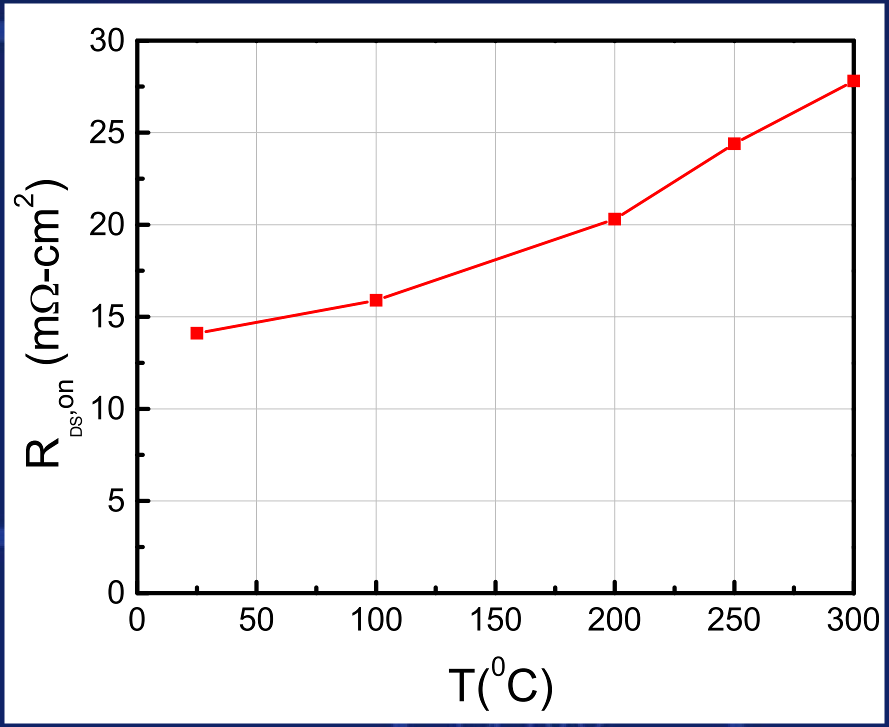


V_{TH} Reduces from 4 V to 2 V at 175°C



High Temp DC Data – R_{ON} doubles at 300°C





Comparison of Switching Energy of 1200V SiC DMOSFET and Si IGBT

	Turn-on 25 ºC	Turn-on 150 ºC	Turn-off 25 ºC	Turn-off 150 ºC
SiC MOSFET	201 µJ	173.5 µJ	57.8 µJ	60.2 µJ
Si IGBT	239 µJ	315 µJ	565.9 µJ	1200 µJ

- SiC MOSFET total switching loss:
  - 258.8 µJ @ 25 ºC
  - 233.7 µJ @ 150 ºC
- Si IGBT total switching loss:
  - 804.9 µJ @ 25 ºC
  - 1515 µJ @ 150 ºC

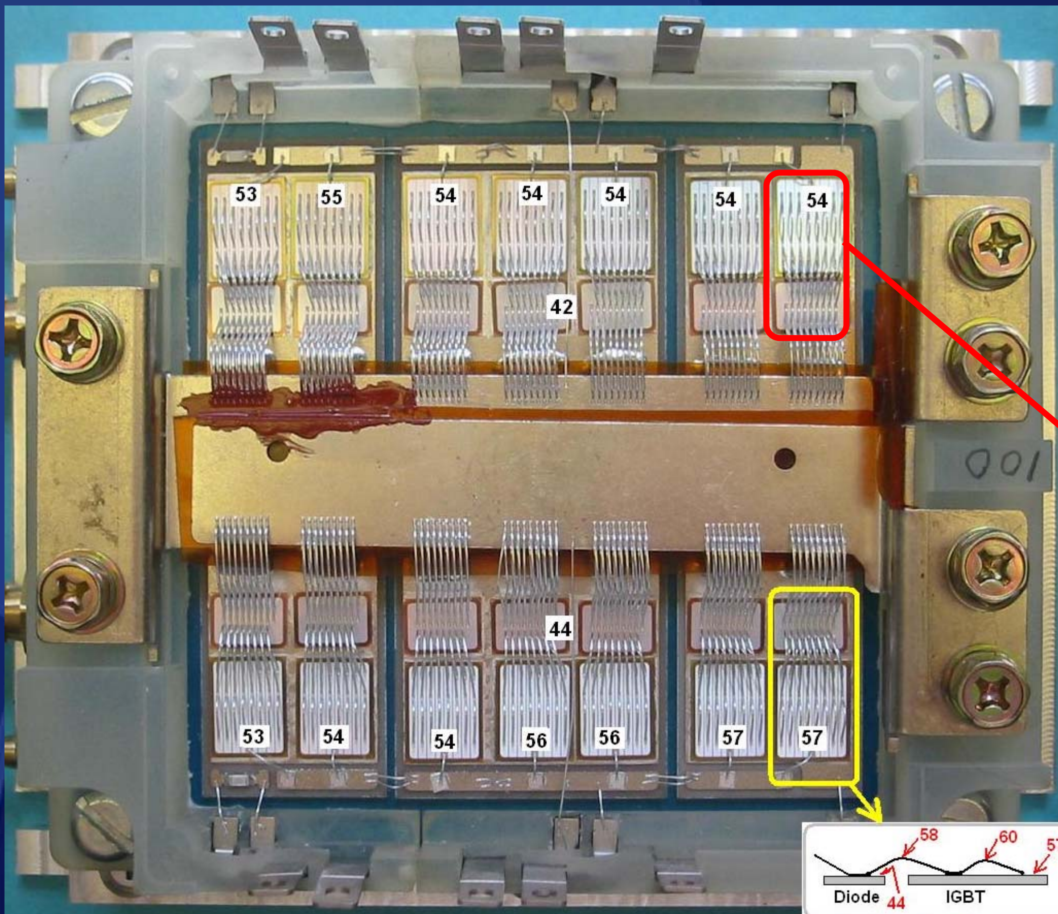
Cree C2D10120 1.2 kV / 10 A SiC Schottky used in both cases as inductor diode

Comparison of Switching Losses of 1200V SiC DMOSFET and Si IGBT

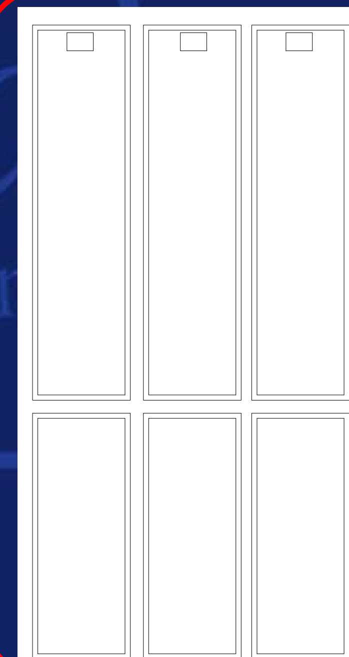
- SiC MOSFET has substantially lower inductive switching losses than competitive Si IGBT especially at high temperature,
  - At 25 ºC, total inductive switching loss of SiC DMOSFET is less than 1/3 of Si IGBT
    - Turn-on losses are similar and turn-off losses are about 1/10 of Si IGBT
  - At 150 ºC, total inductive switching loss of SiC DMOSFET is less than 1/6 that of a Si IGBT
    - Turn-on losses are about 1/2 and turn-off losses are about 1/20 of Si IGBT

- Next Steps ⇒
  - Scale Up & Cost Reduction
  - Insertion Into SiC Power Modules
- Primary Concern ⇒ Yield

All SiC Dual 1200V/1400A Module w/ 67A MOSFET Die



- Replace each 12x15.6 mm Si IGBT with 3.7mm x 14.5mm SiC MOSFET
- Replace each 12x8.5mm Si FWD with 3.7x 9.5mm SiC JBS Diode

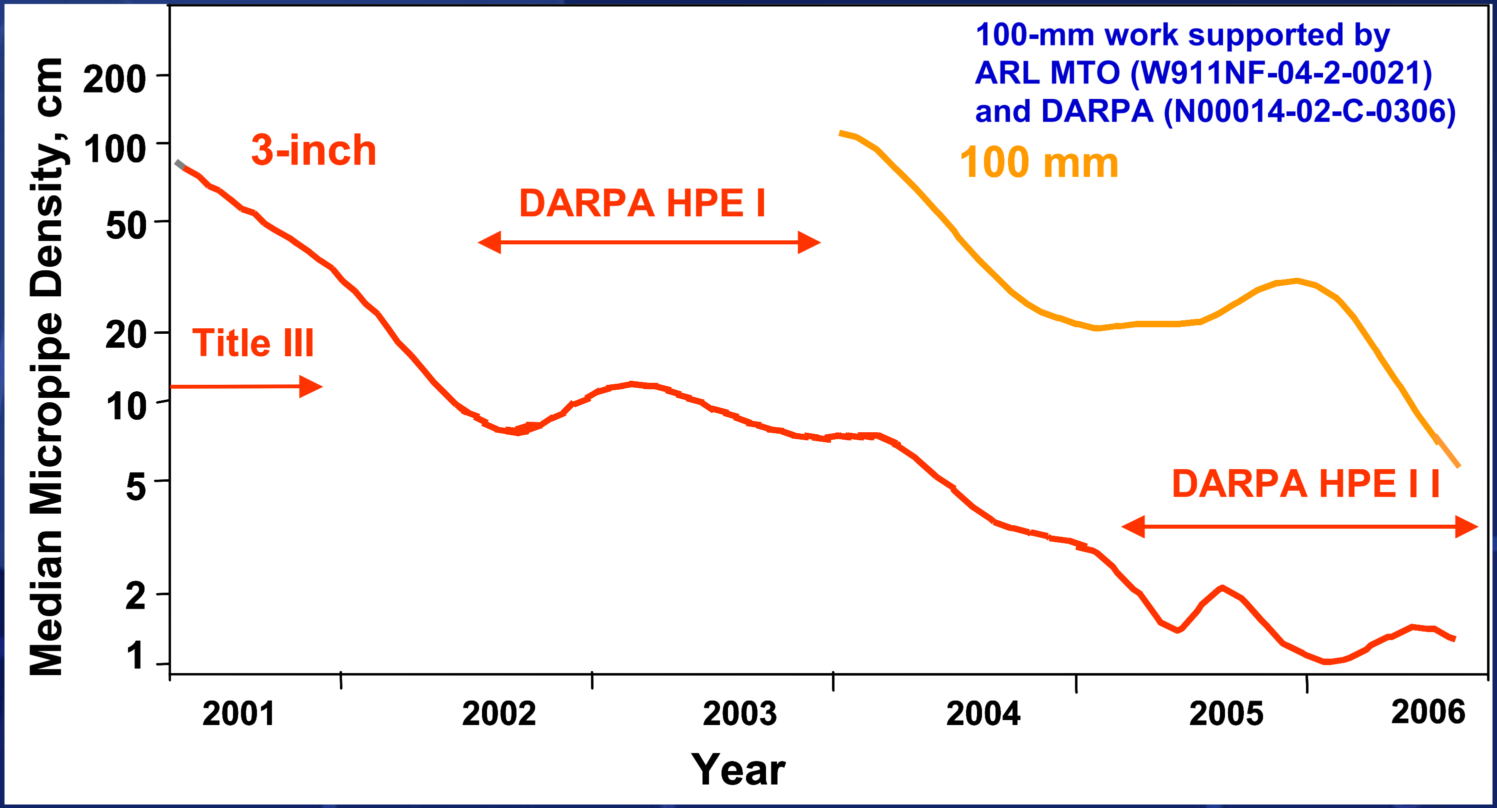


- 67A SiC MOSFET – 53mm^2, 150A/cm^2, V_f = 1.5 V @ 25°C, V_f = 2.0 V @ 175°C
- 53A SiC JBS Diode – 35mm^2, 150A/cm^2, V_f = 1.8 V @ 25°C, V_f = 2.2 V @ 175°C

Producibility of 1200V SiC Power Devices

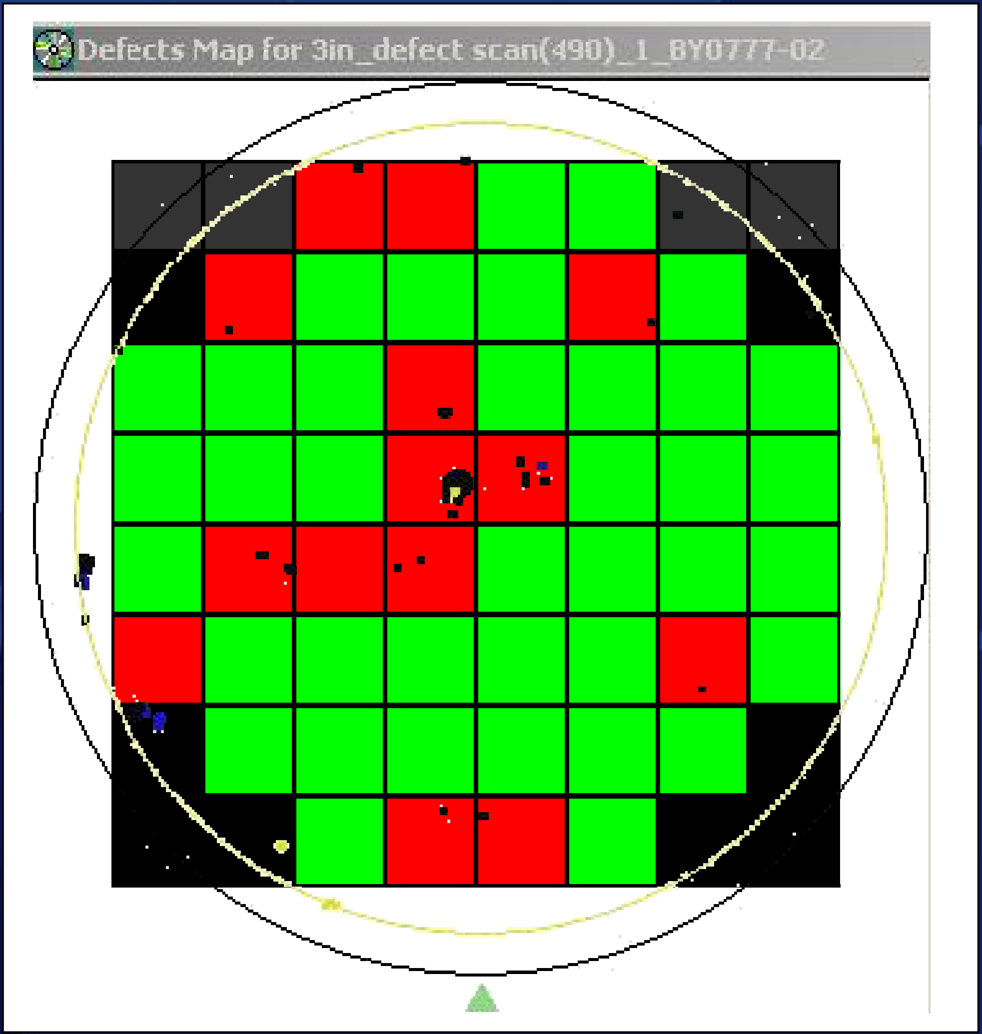
- High Quality SiC Material for SiC Power Devices
  - Reduced 4HN-SiC Micropipe Density for Increased SiC Power Device Yield
  - Pre-Screening of SiC Substrate and Epi Material for Enhanced SiC Power Device Yield
- Improved SiC Power Device Fabrication
- Large Area SiC DMOSFET Devices
  - 10A/9kV SiC DMOSFETs
- SiC DMOSFET Stability and Reliability

Cree SiC Micropipe Density Dramatically Reduced For Enhanced SiC Device Yield



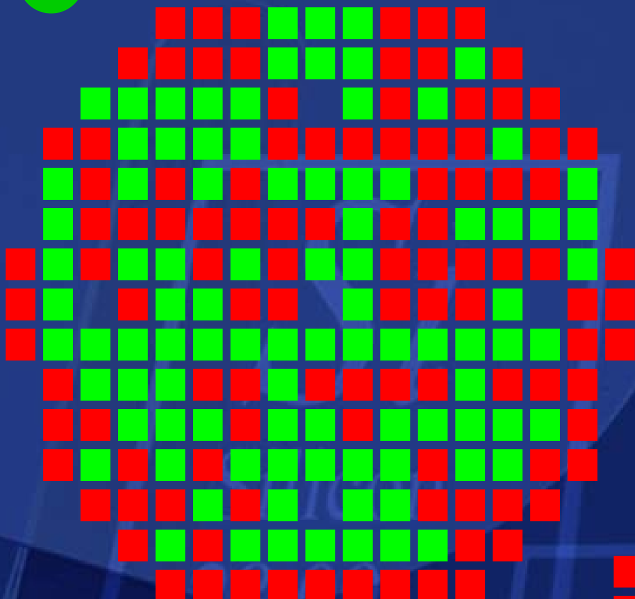
- Cree Monthly Median Production SiC Substrate Micropipe Density (MPD)
- Zero Micropipe Density 3-inch 4HN SiC Wafer Demonstrated!

Pre-Screening of SiC Material To Maximize SiC Device Yield



- **Distribution of Catastrophic SiC Material Defects Determined by Candella Tool**
  - SiC substrate & epi defects
  - 2.31 defects cm^{-2} on this wafer
- **Project 8x8 mm SiC Devices on Candella Material Defect Map**
- **Provides Estimate of SiC Device Yield From Material Defect Distribution**
  - 73% material yield on this wafer

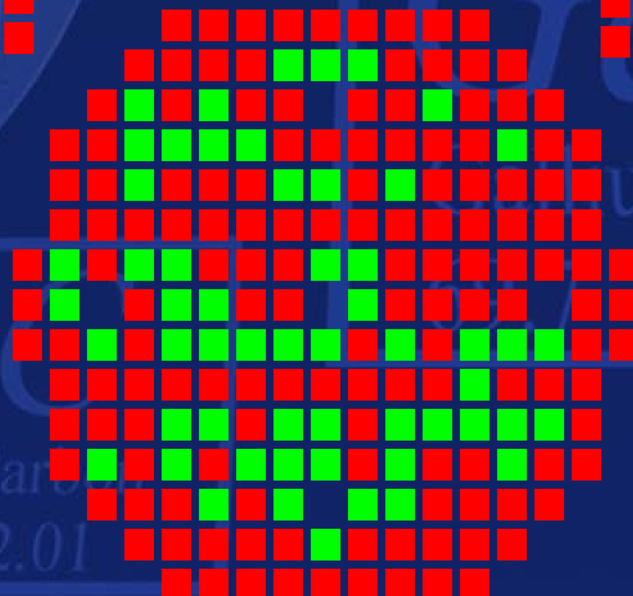
15A/1200V SiC DMOSFET Device Yield Maps



1200V Blocking Yield

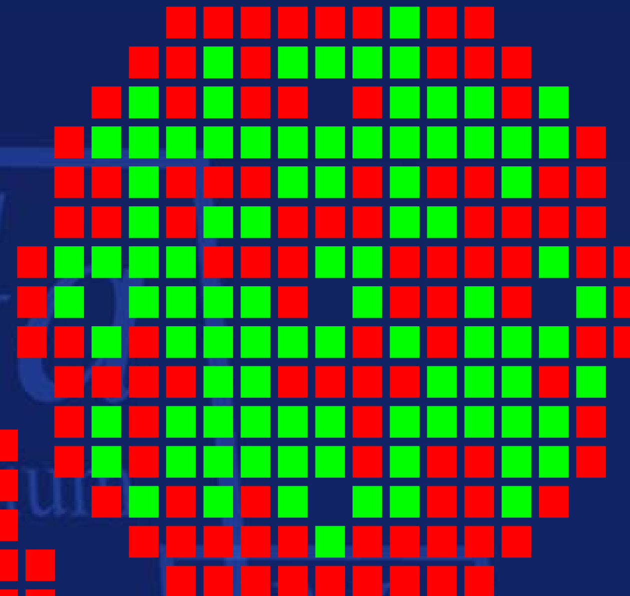
$I_{DS} < 100\ \mu A$

46.5%



Combined Yield

27.7%



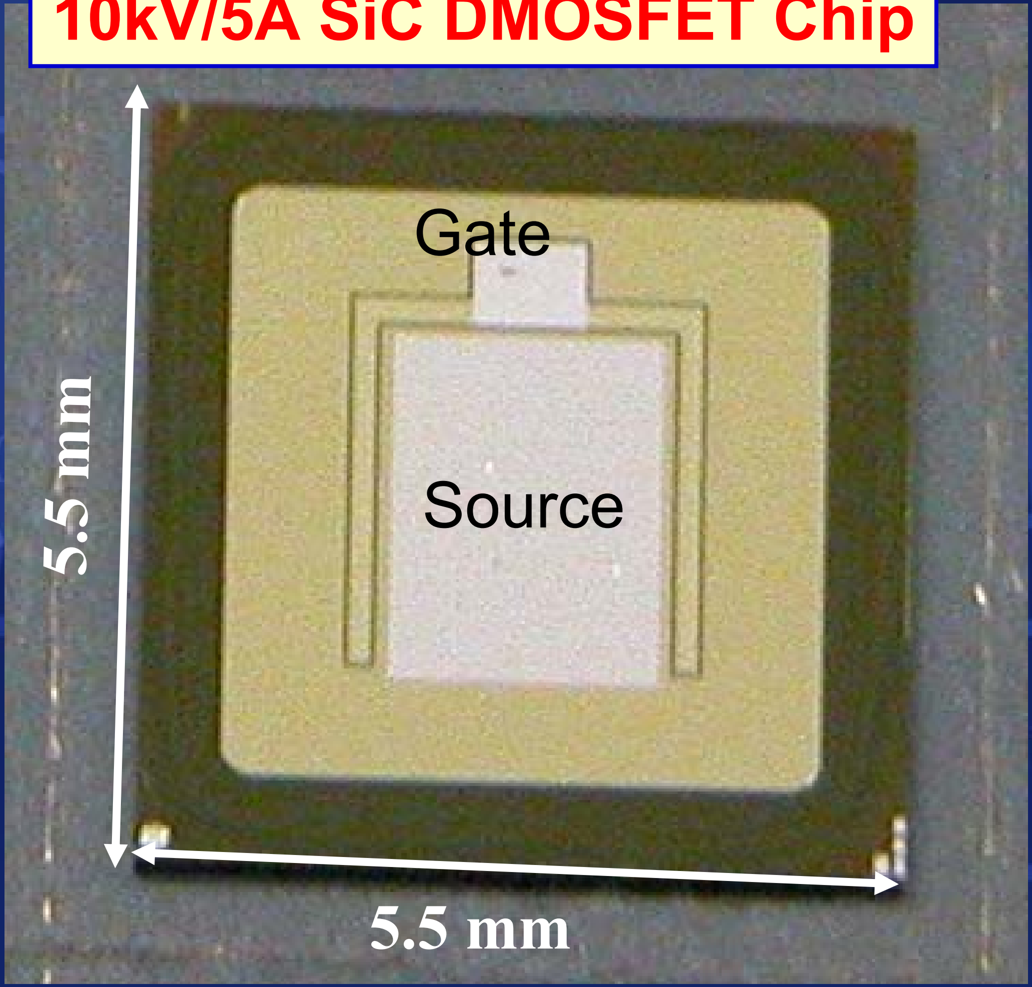
On-State Yield

$I_{DS} > 3$ A at $V_G = 15$ V and $V_{DS} = 0.5$ V

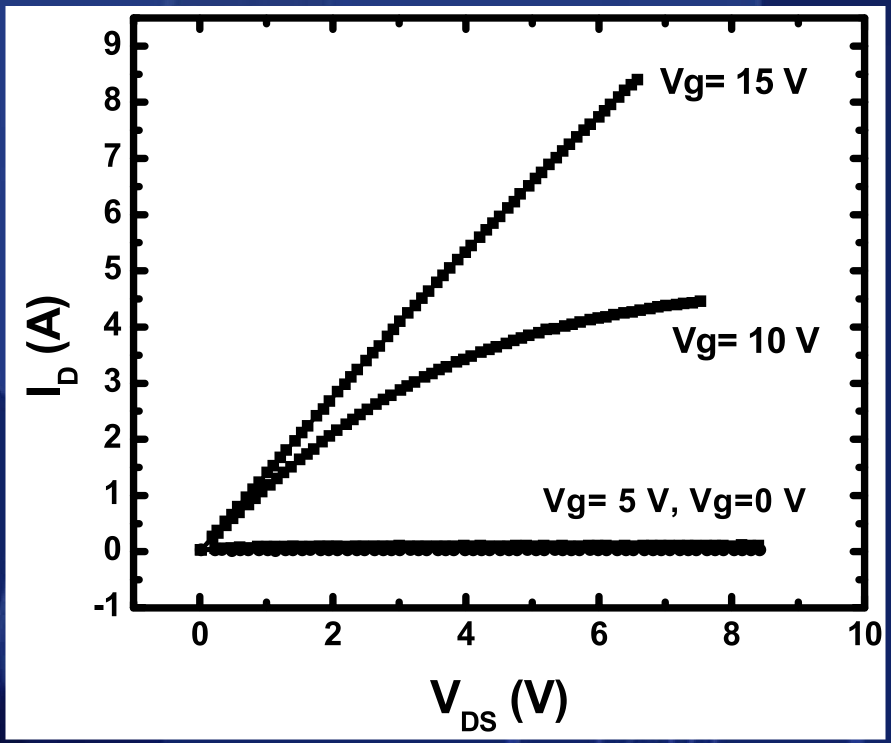
46.0%

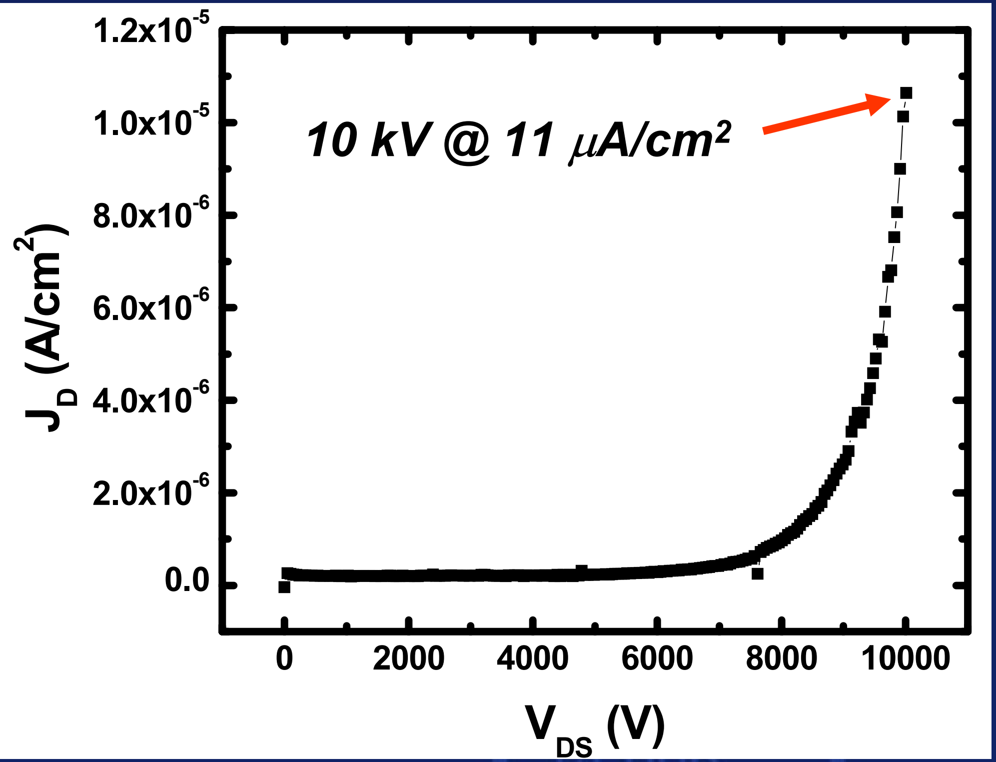
10kV SiC DMOSFET Area Scaled Up By Factor of 36x During HPE-II

10kV/5A SiC DMOSFET Chip



10kV/5A 4H-SiC DMOSFET
Forward & Reverse Characteristics

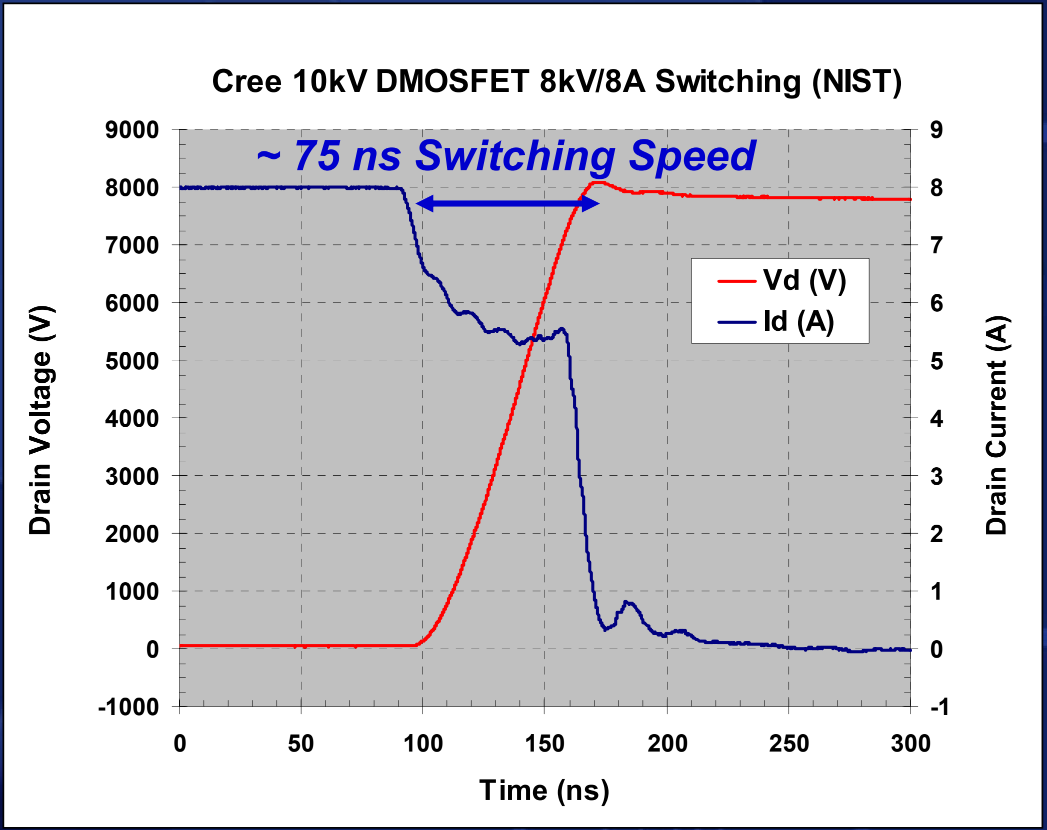




$R_{on,sp}$ = 111 mΩ-cm²
V_F @ 5A = 3.9 V

BV > 10 kV

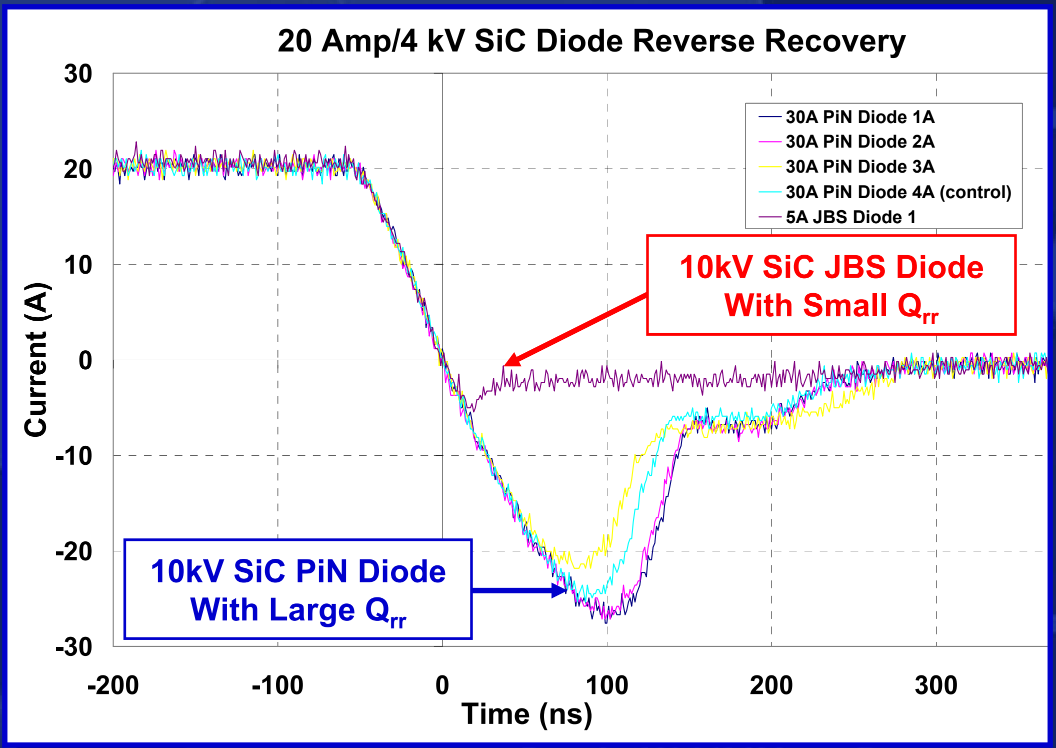
10kV SiC DMOSFET Demonstrated For 20 kHz Switching of SiC Module



Measured Switching Speed of ~ 75 ns for 10kV SiC DMOSFET at 25°C

- 10kV/10A SiC DMOSFETs Have Been Demonstrated
- 10kV SiC DMOSFETs Capable of T_j = 200°C Operation
- 10kV SiC DMOSFETs Have Switching Speed ~ 75 ns
- Enables 20kHz Switching of 10kV SiC Half H-Bridge Module
- Remaining Issue – 10kV SiC DMOSFET Needs to Be Scaled Up to 20A with 30% Yield

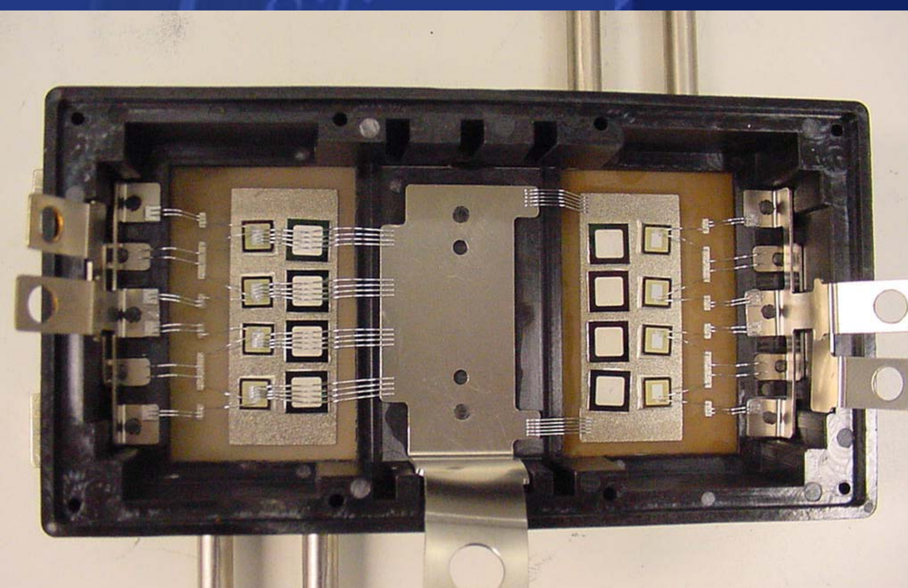
10kV SiC JBS Diode Demonstrated For 20 kHz Switching of SiC Module

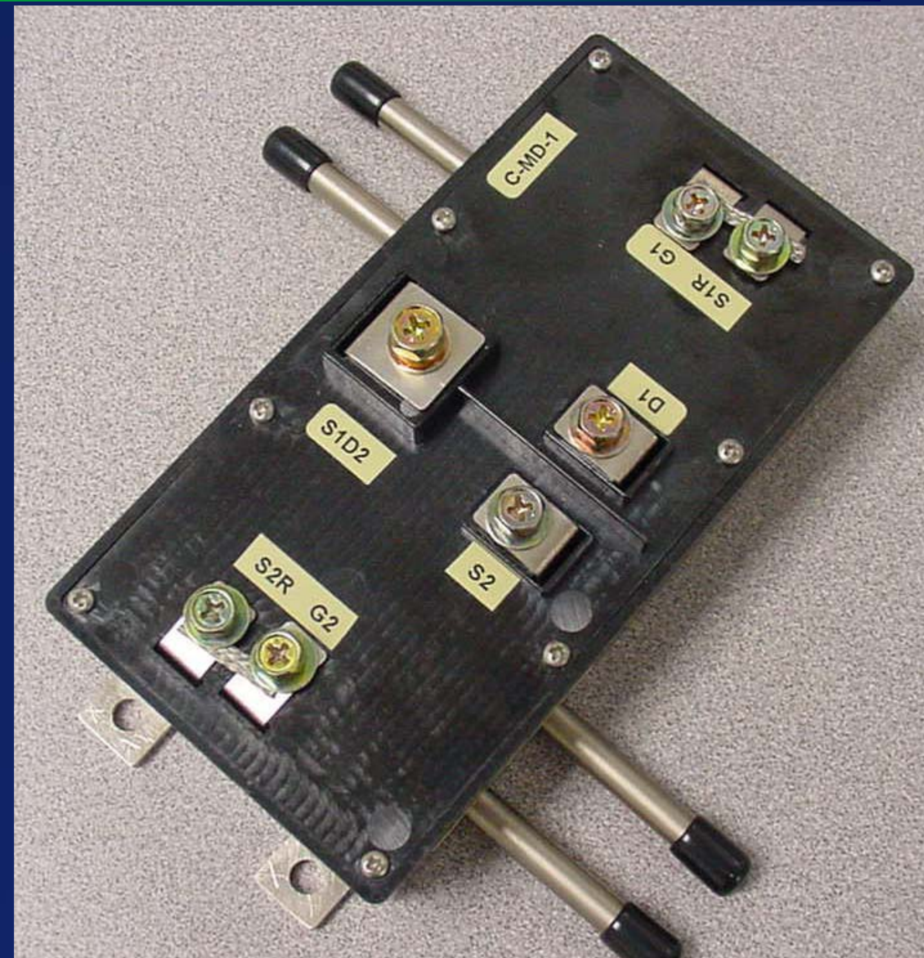


10kV/20A SiC JBS Diode Has Much Smaller Reverse Recovery and Higher Switching Speed Compared to PiN

- SiC PiN Reverse Recovery Energy Dissipated On SiC DMOSFET
- Solution - Use SiC Junction Barrier Schottky (JBS) Diodes With Much Smaller Reverse Recovery (Q_{rr}) and Higher Switching Speed
- HPE-II Refocused on 10kV/20A SiC JBS Diodes
- 10kV/5A SiC JBS Diodes Have Been Demonstrated with Single Wafer Blocking Yield > 40%
- Remaining Issue – 10kV SiC JBS Diode Needs to Be Scaled Up to 20A with 30%Yield

10kV 20A Dual SiC MOSFET Module





MTO DARPA MICROSYSTEMS TECHNOLOGY OFFICE

POWEREX

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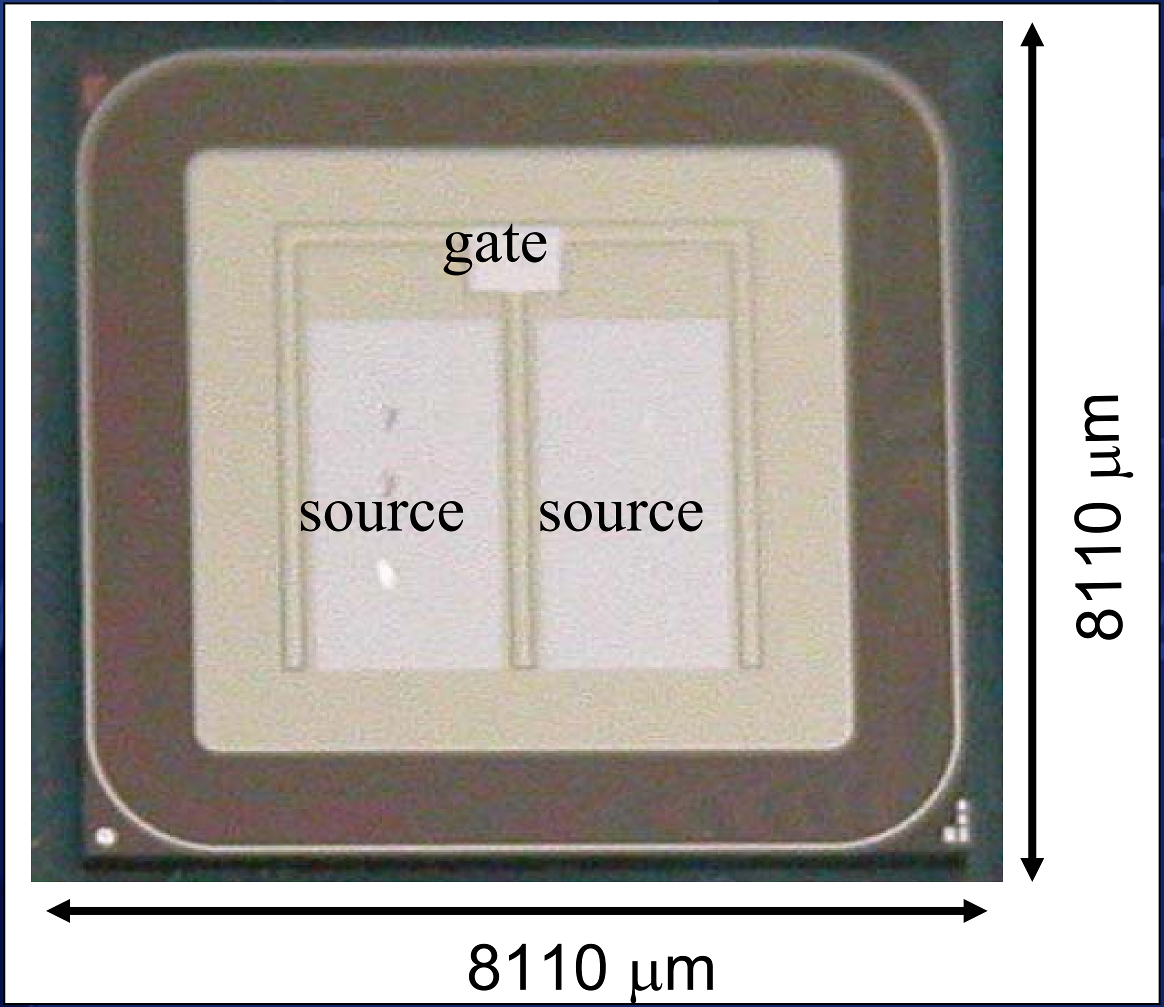
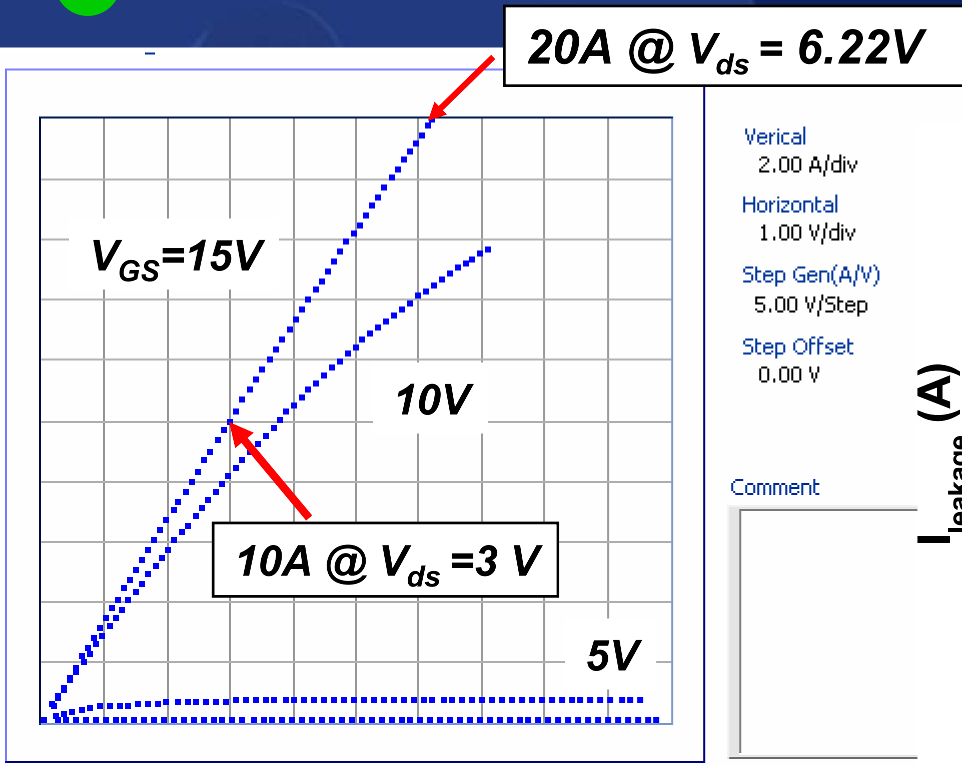
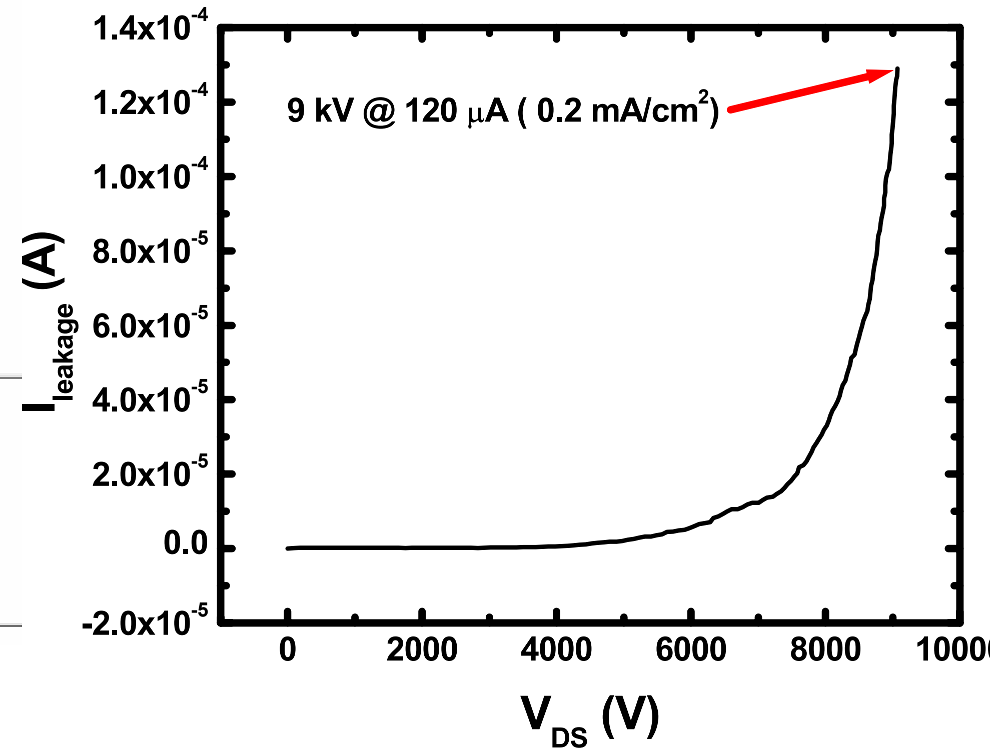
Demonstrated Capability of Fabricating Large 9kV SiC DMOSFET Devices



- 9 kV / 20 A SiC DMOSFET
- 8.1 x 8.1 mm^2 Chip Area
- 0.31 cm^{-2} Active Area

9kV/20A 4H-SiC DMOSFET Demonstrated

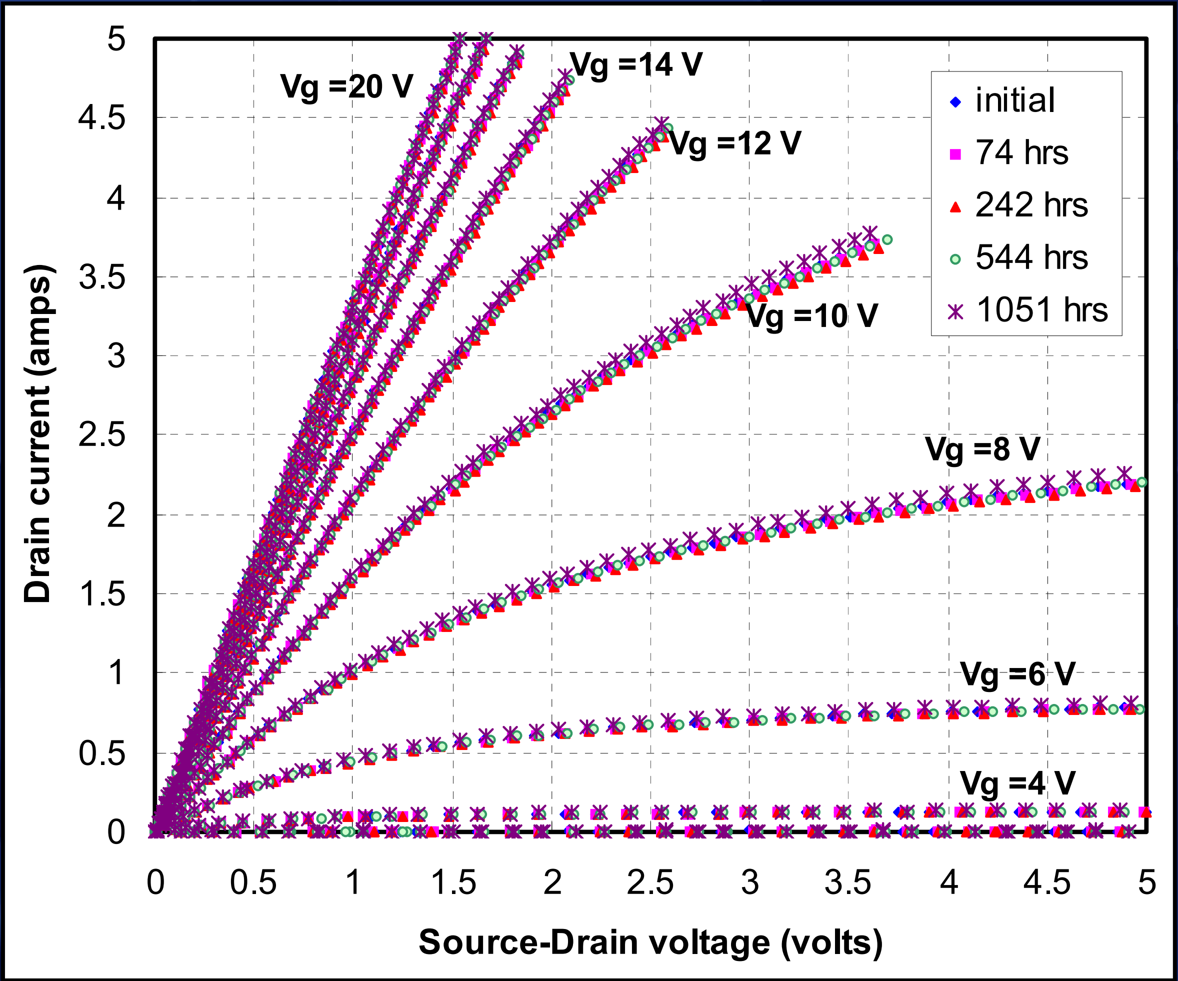




91 mΩ-cm^2
20 A @ 189 W/cm^2

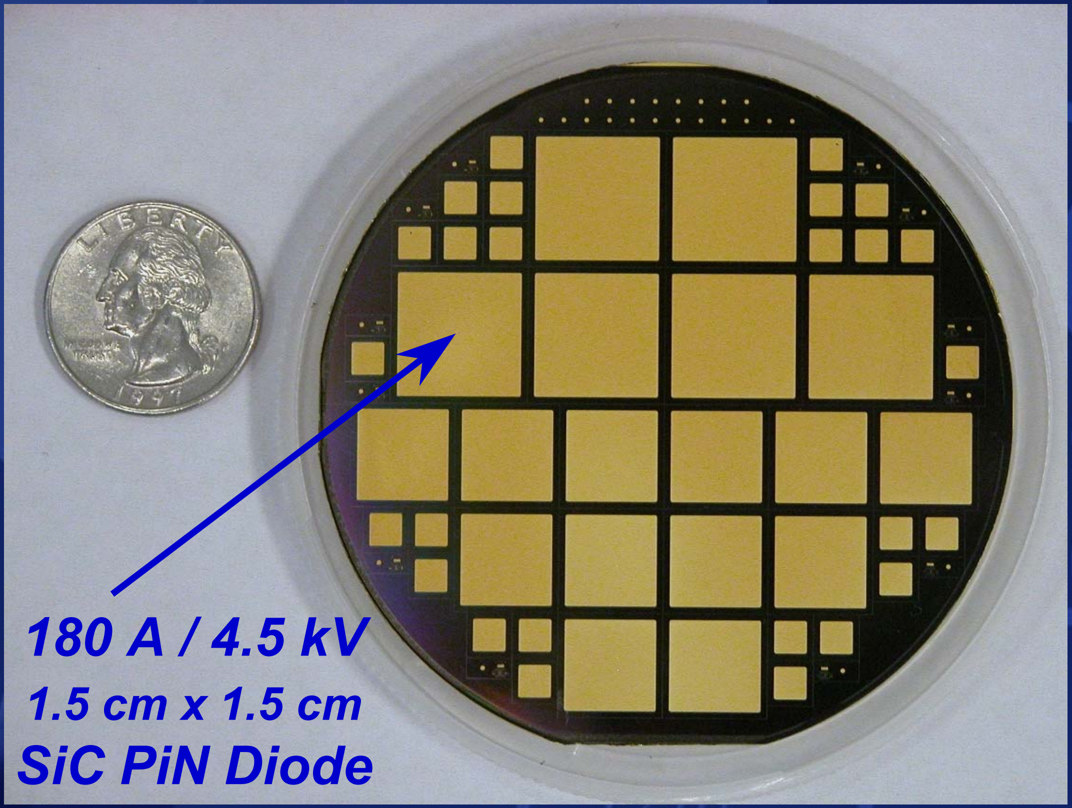
BV > 9 kV

Stability of 1200V/5A SiC DMOSFETs Under High Temp Forward Gate Bias Stress



- Forward Gate Bias Stress of Packaged 1200V/5A SiC DMOSFETs (0.0753 cm^2)
  - Stressed at 175°C - V_g = 15 V
  - Source/Drain Grounded
  - Similar to Si MOSFET Stress Test Adjusted for Oxide Field
- SiC DMOSFETs Cooled to RT and Remeasured
- 1200V SiC DMOSFET I-V Curve Remains Virtually Unchanged Up To ~ 1050 Hrs High Temp Forward Gate Stress

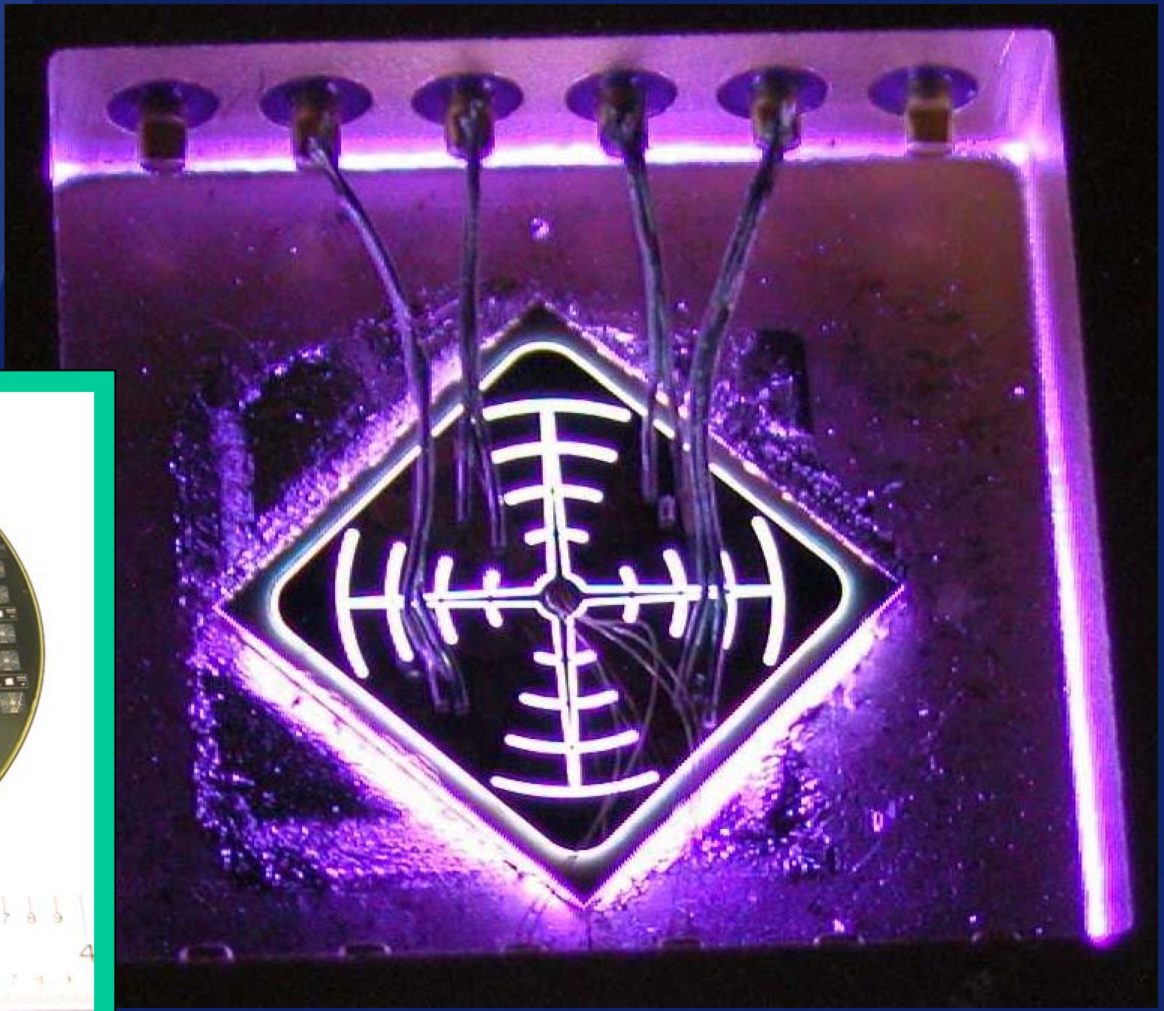
180 A / 4.5 kV SiC PiN Diode

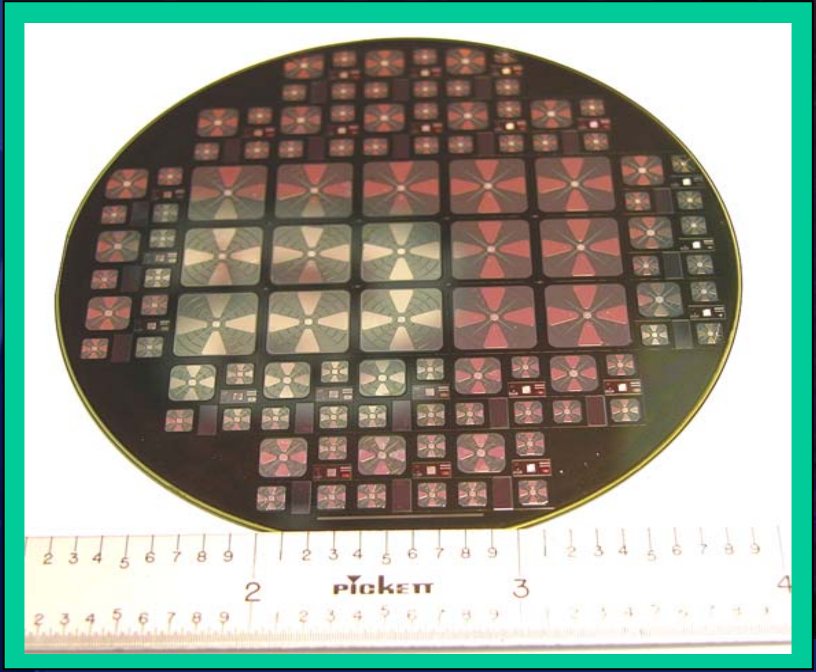


- Largest SiC Device Demonstrated
- Over 65% Device Yield
  On 3-inch 4HN-SiC Wafer
- 1.5 cm x 1.5 cm SiC PiN Diode
  Blocking Voltage Limited by
  Thinner Blocking Layer
- Result of High Quality Material
  Growth and Device Fabrication
- Demonstrates That Large Area
  SiC Power Devices Can Be
  Fabricated With Good Yield

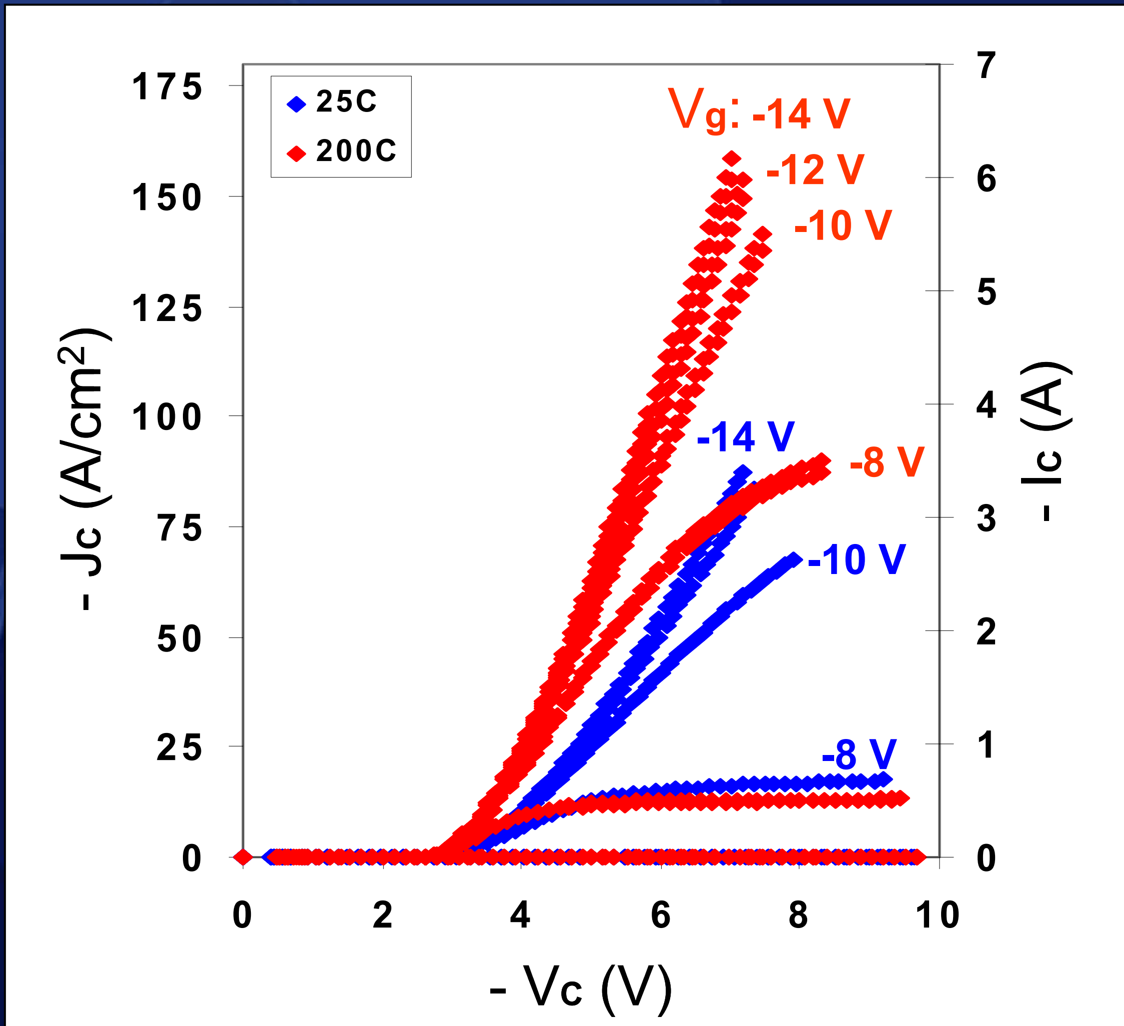
1 cm x 1 cm SiC Thyristor

5 kV / 300 Amp
4H-SiC
Thyristor





2mm x 2mm 7.5 kV 4H-SiC p-IGBT Forward Characteristics



- **Active area:**

  2mm x 2mm

- **At 25°C**
  - $R_{diff,\ on}$: 38.8 mΩ·cm²
  - V_F @ 50A/cm²: 5.8 V
- **At 200°C**
  - $R_{diff,\ on}$: 22.6 mΩ·cm²
  - V_F @ 50A/cm²: 4.7 V

μ_{ch} ~ 10 cm²/V-s

V_{TH} = -7.6 V

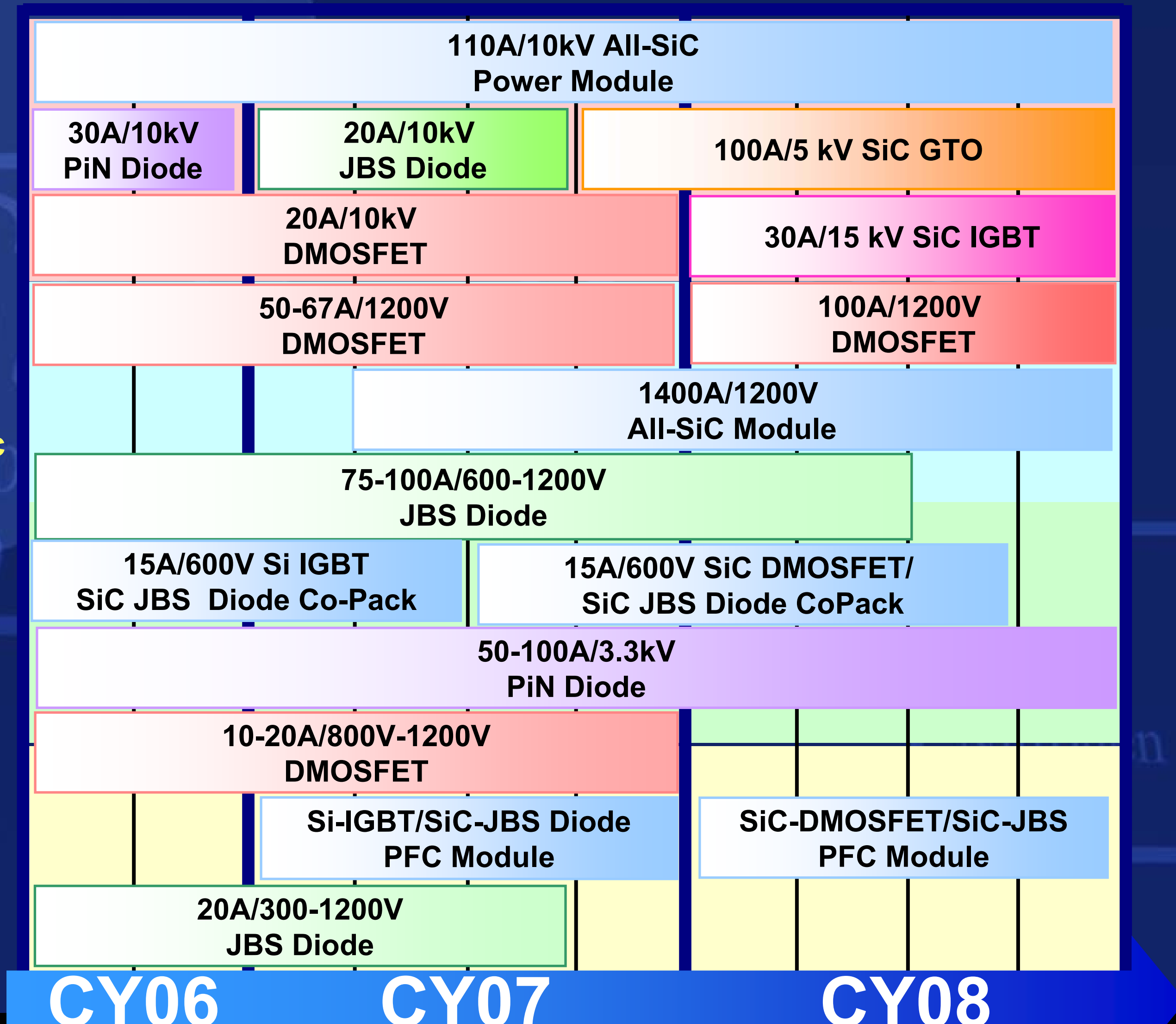
SiC Power Technology Roadmap

Power Distribution

Hybrid-Electric Vehicle

Motor Control

Power Supplies



CREE

Creating Technology That Creates Solutions

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Creating Technologies That Create Solutions

Silicon Carbide The Material Difference

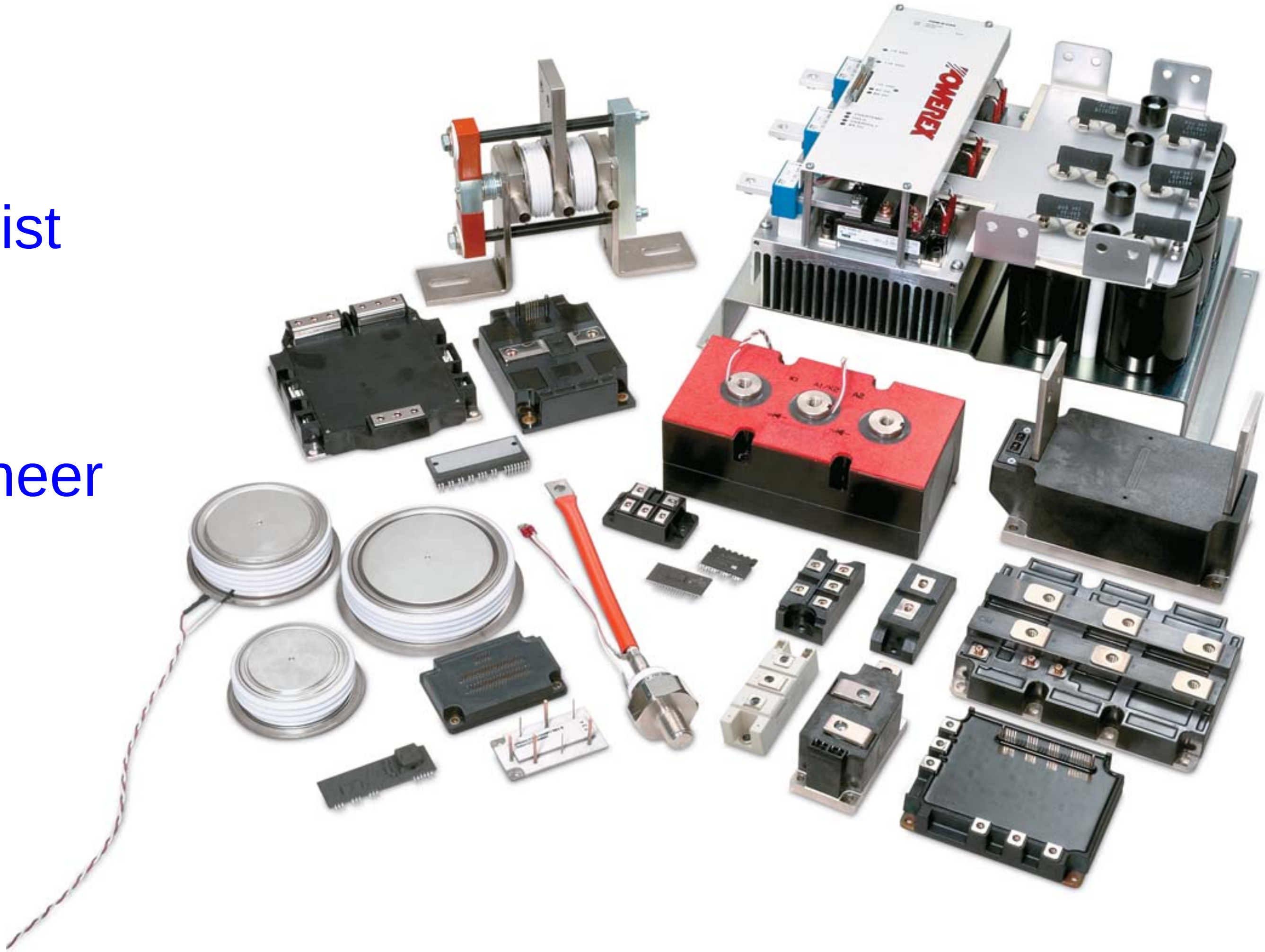
Session 4b

Leslie

Power Module Packaging & Integration

Scott Leslie
Chief Technologist

John Donlon
Applications Engineer

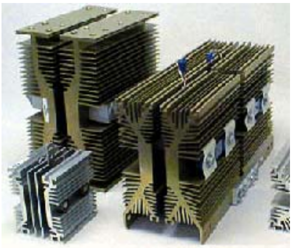


Power Semiconductor Module Integration - Outline

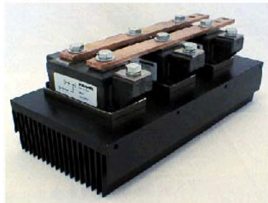
- Trends in IGBT Chip Technology
  - Size, Voltage, Power Losses & Frequency
  - Impact on Packaging
- Intelligent Power Modules
  - Integrating Gate Drive & Protection Features in the Module Package
- System in a Module
  - Further Integration of System Components within a Module Package
- High Voltage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

Power Semiconductor Device Evolution

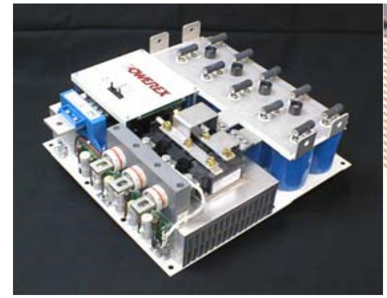
Discrete Assemblies



Module Assemblies



Complete Power System
Standard & Application Specific



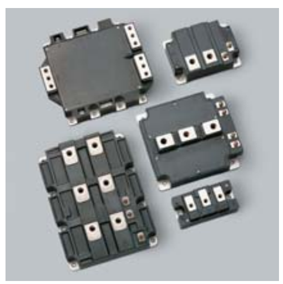
Powerex
Pow-R-Pak

Semikron
Skiip Pak

SCR / Diode /
GTO Discretes

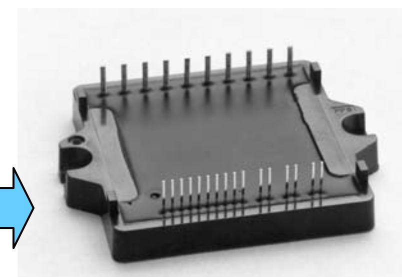
SCR / Diode Modules

BJT / MOSFET
Discretes



Darlington Transistor /
MOSFET / IGBT Modules

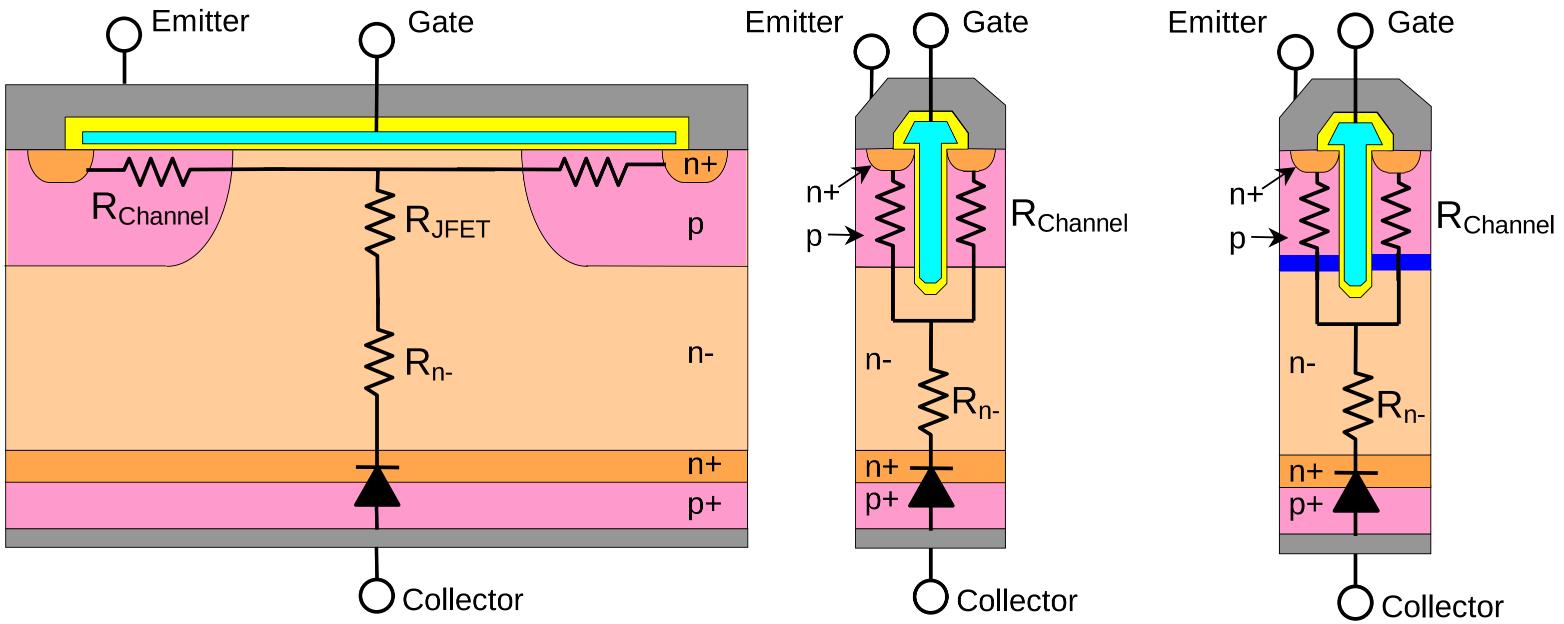
Intelligent IGBT Modules
(IPM)



Application Specific IPM

Power Switch → **Electrical Isolation Integrated** → **Gate Drive & Protection Integrated** → **Low Power System in a Module** → **High Power System**

IGBT Chip Design Evolution



Horizontal Gate Channel

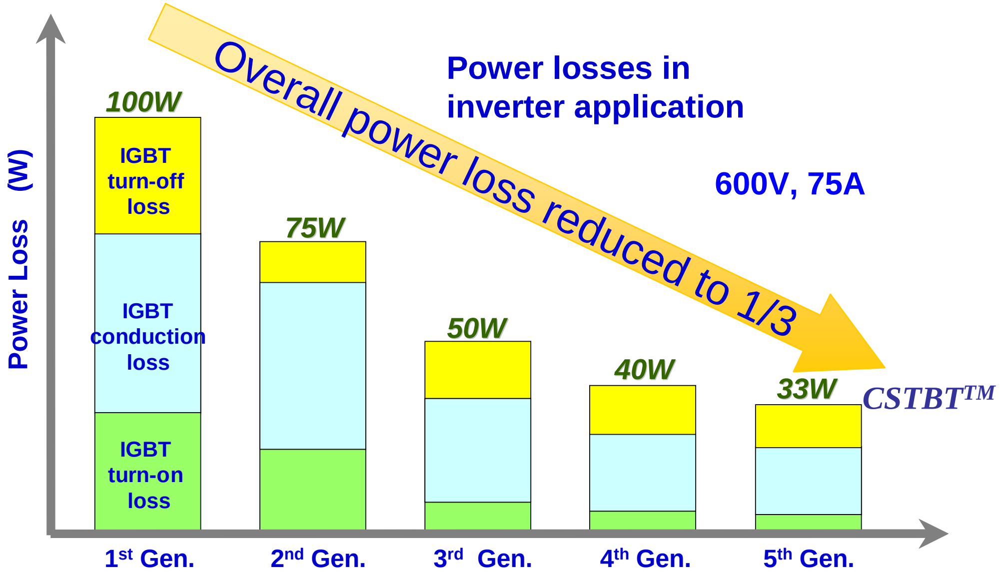
Vertical Gate (Trench) Design

CSTBT Design

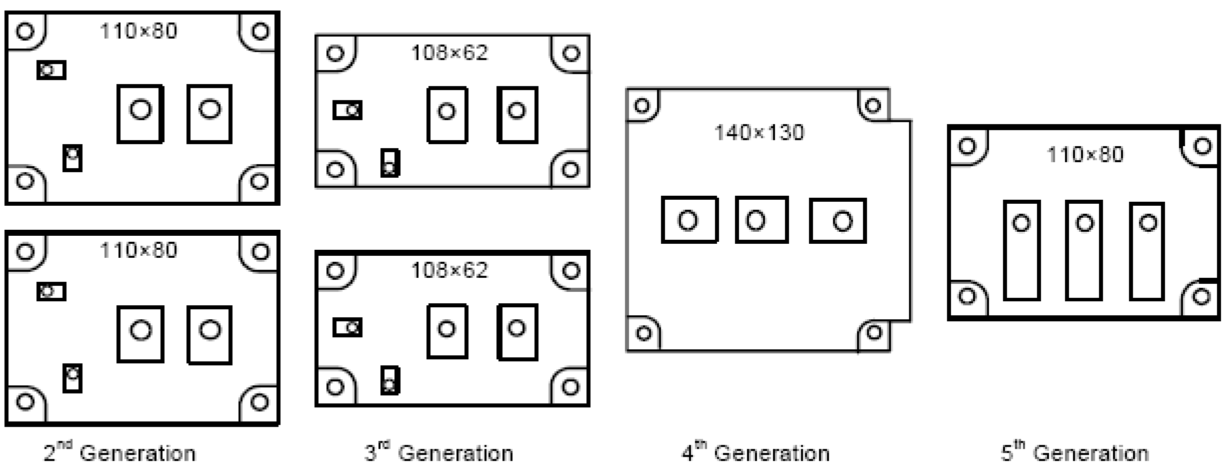
- Vertical channel requires less area compared to the horizontal channel of planar structure
- No R_{JFET} between adjacent cells

- **Greater cell density**
- **More uniform current flow through chip**
- **Robust Turn-Off Switching Capability**
- **Greater cell density**
- **Lower $V_{CE(SAT)}$**

More Switching Power in a Smaller Package

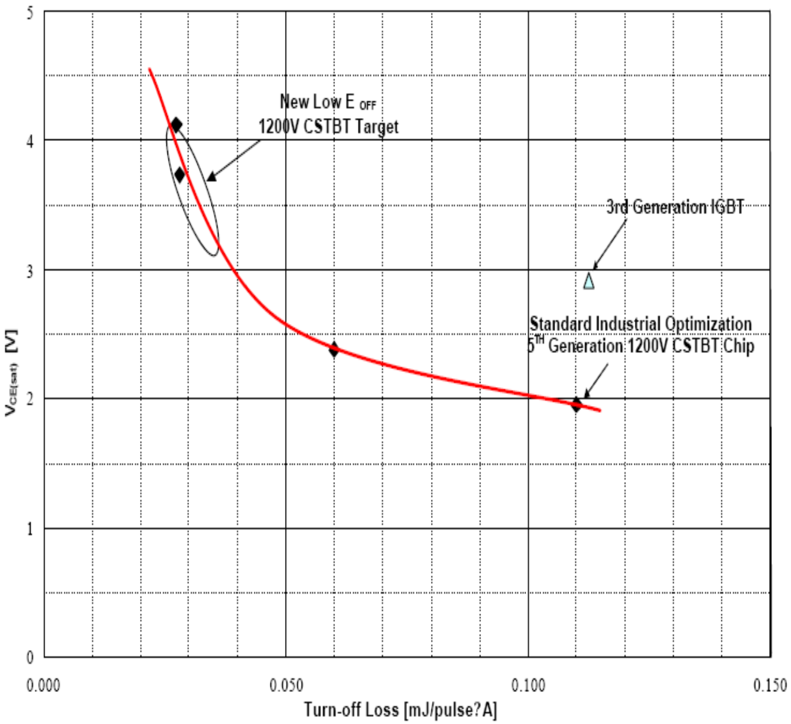


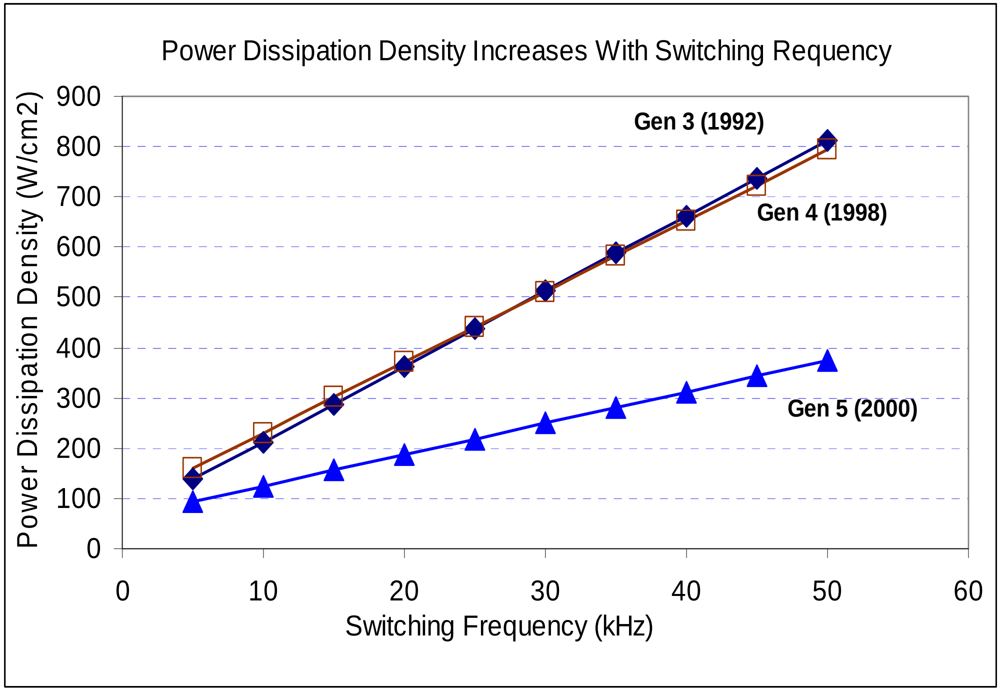
50 – 60% Reduction in Module Footprint Due to Decrease in IGBT Chip Losses Over Last 15 Years



1200V, 400A IGBT Module in Half H-Bridge Configuration

IGBT Switching Frequency Now Up to 50 kHz



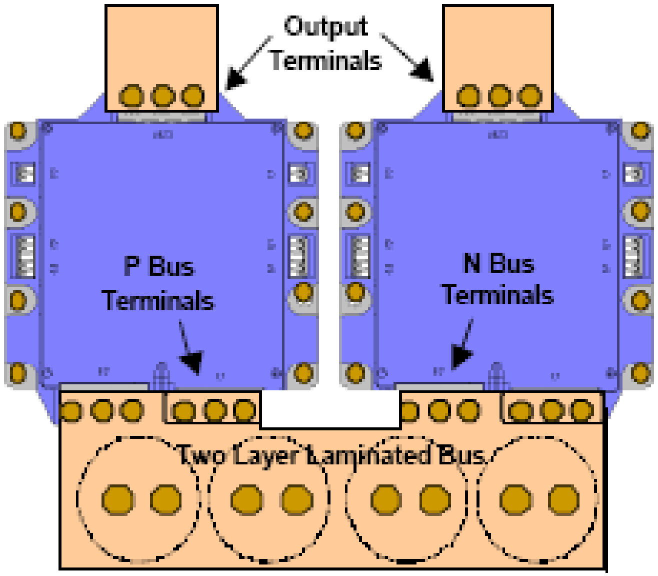


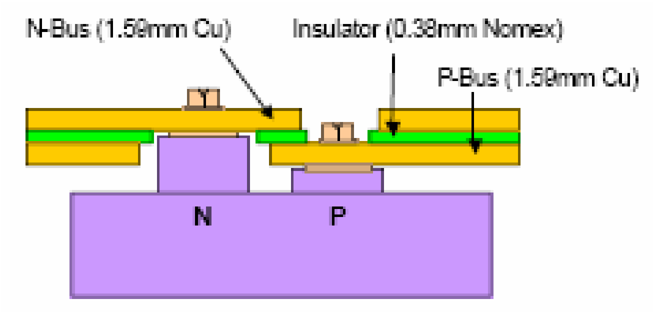
Conduction vs Switching Loss Trade-Off

Vcc = 600V, Ic = 100A, 50% Duty Cycle -- Calculated

Module Design Reduces System Inductance & Complexity

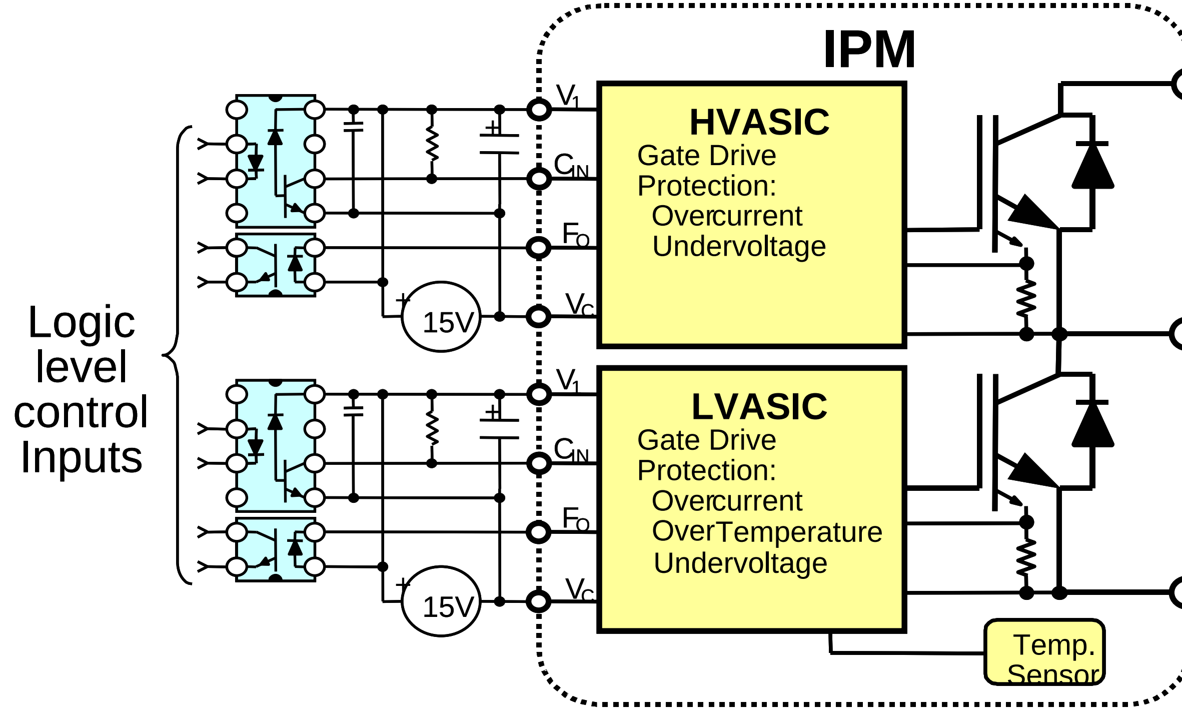
1200V, 900A Mega Power Dual IGBT Module with Internal Laminated Bus

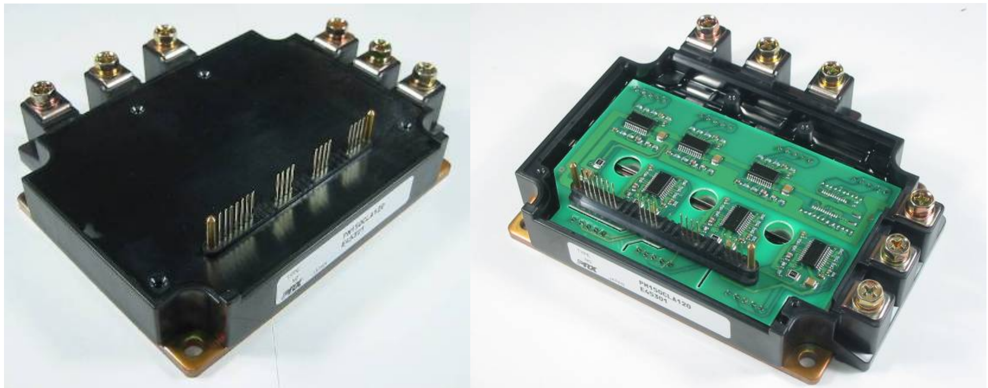




Integrated "Intelligent" Power Module = IGBT + Smarts

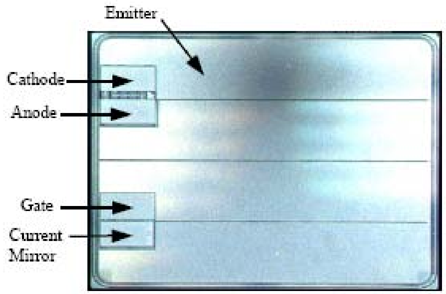
- Gate drive, temperature sensing & protection elements are integrated in the power switch package
- Protection for:
    - **Overtemperature**
    - **Overcurrent & short circuit**
    - **Low/high gate supply voltage**
    - **Fault signal feedback**
- Improves switch performance since protection functions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



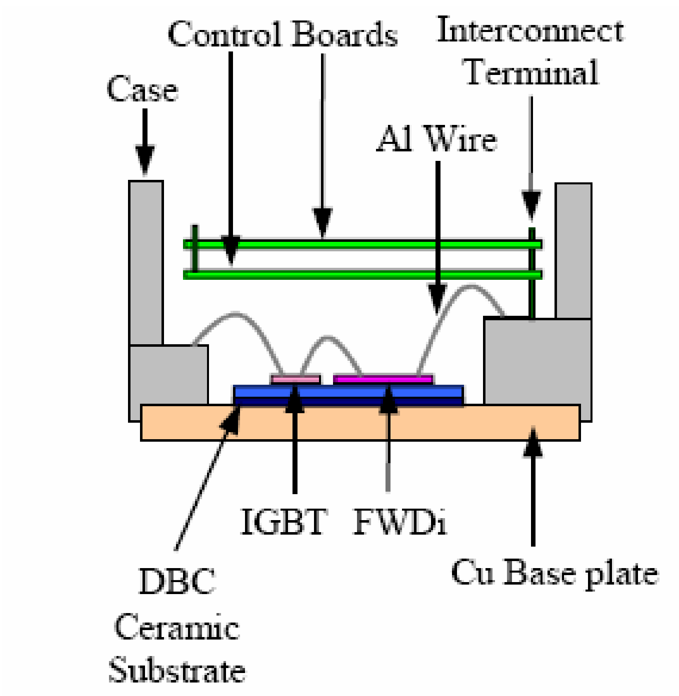


Intelligent Power Modules

IGBT Module Integration – Sensing & Protection

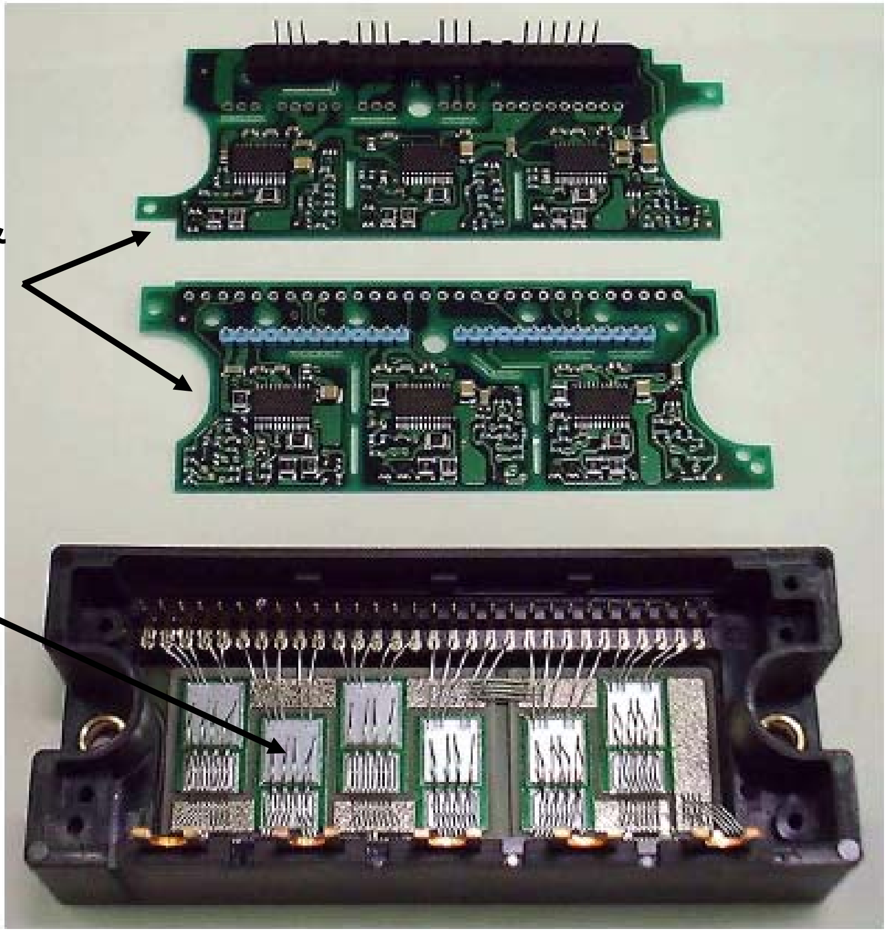


On chip current & temperature sensing



Gate drive & protection circuitry

Power switches



Fault Types & Intelligent Power Module Countermeasures

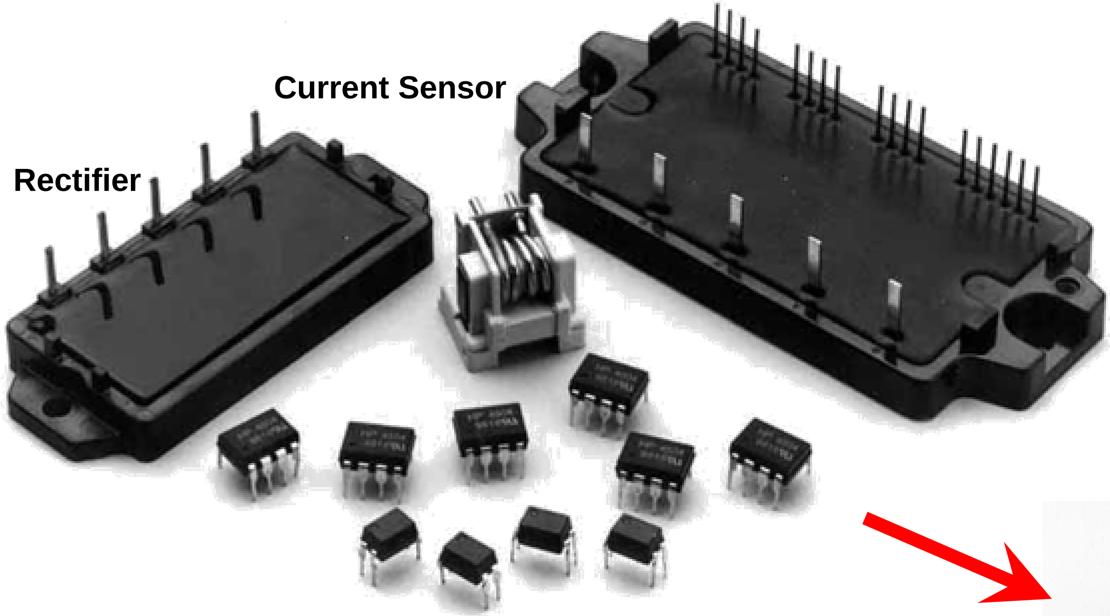
- Chip Overtemperature
  - Gate Drive Turns IGBT Off – Fault Signal Sent to Controller
- Over Current/Short Circuit
  - Short Circuit & RBSOA (Switching Protection)
  - Gate Drive Turns IGBT Off – Fault Signal Sent to Controller
- Gate Drive Supply Under Voltage
  - Gate Drive Turns IGBT Off – Fault Signal Sent to Controller

Complete Power System Integration in a Module

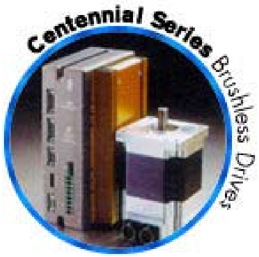
Conventional IPM

Current Sensor

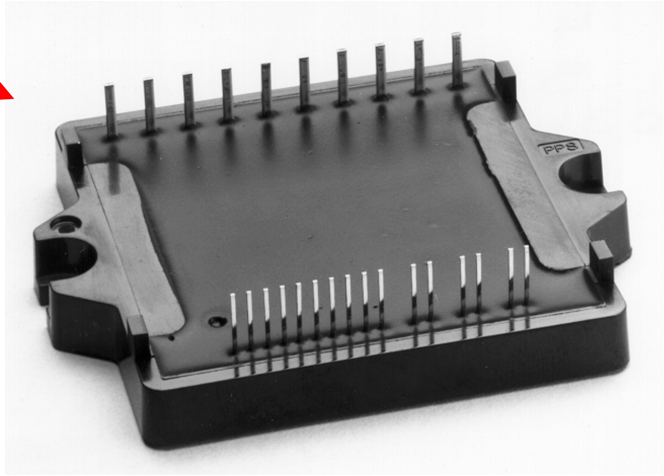
Rectifier



Optocouplers

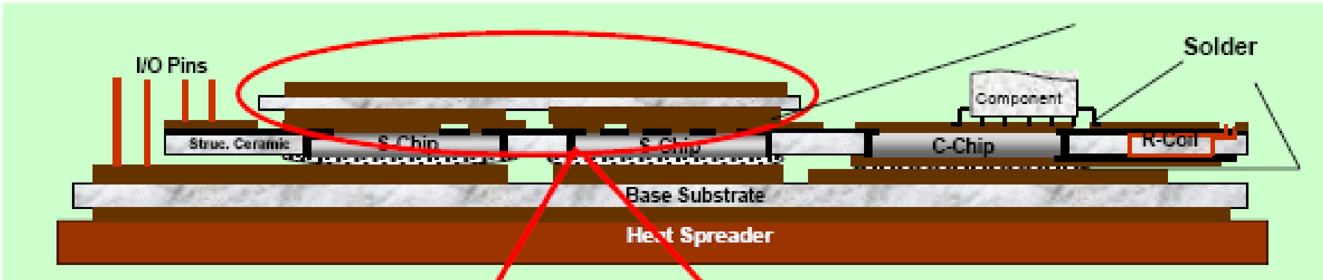


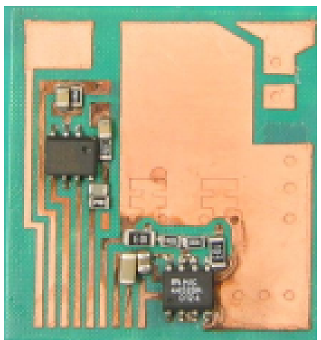
Small 3-Phase Motor Drive System Integrated in an ASIPM Module

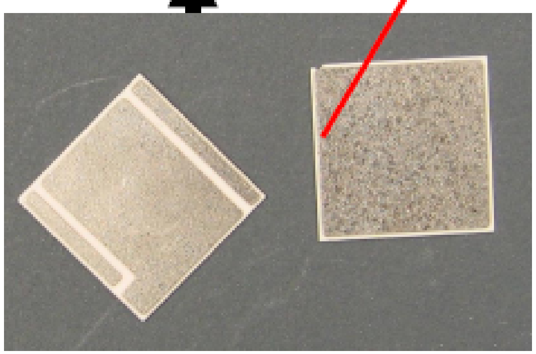


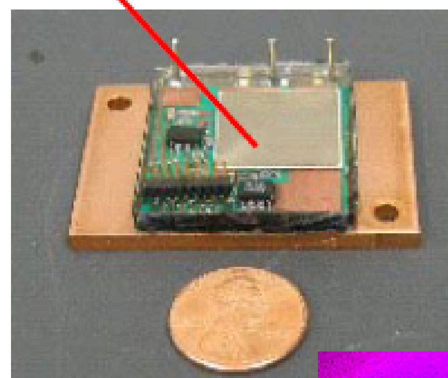
600V, 50A & 1200V, 25A

Integration of Passives in Power Semiconductor Modules

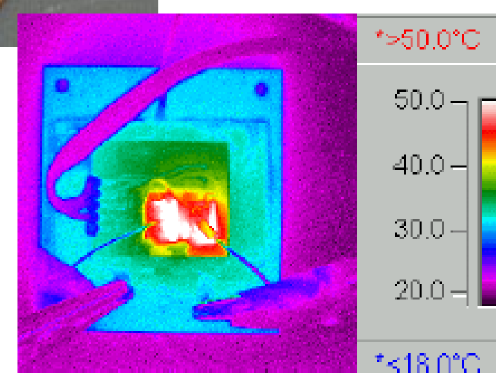




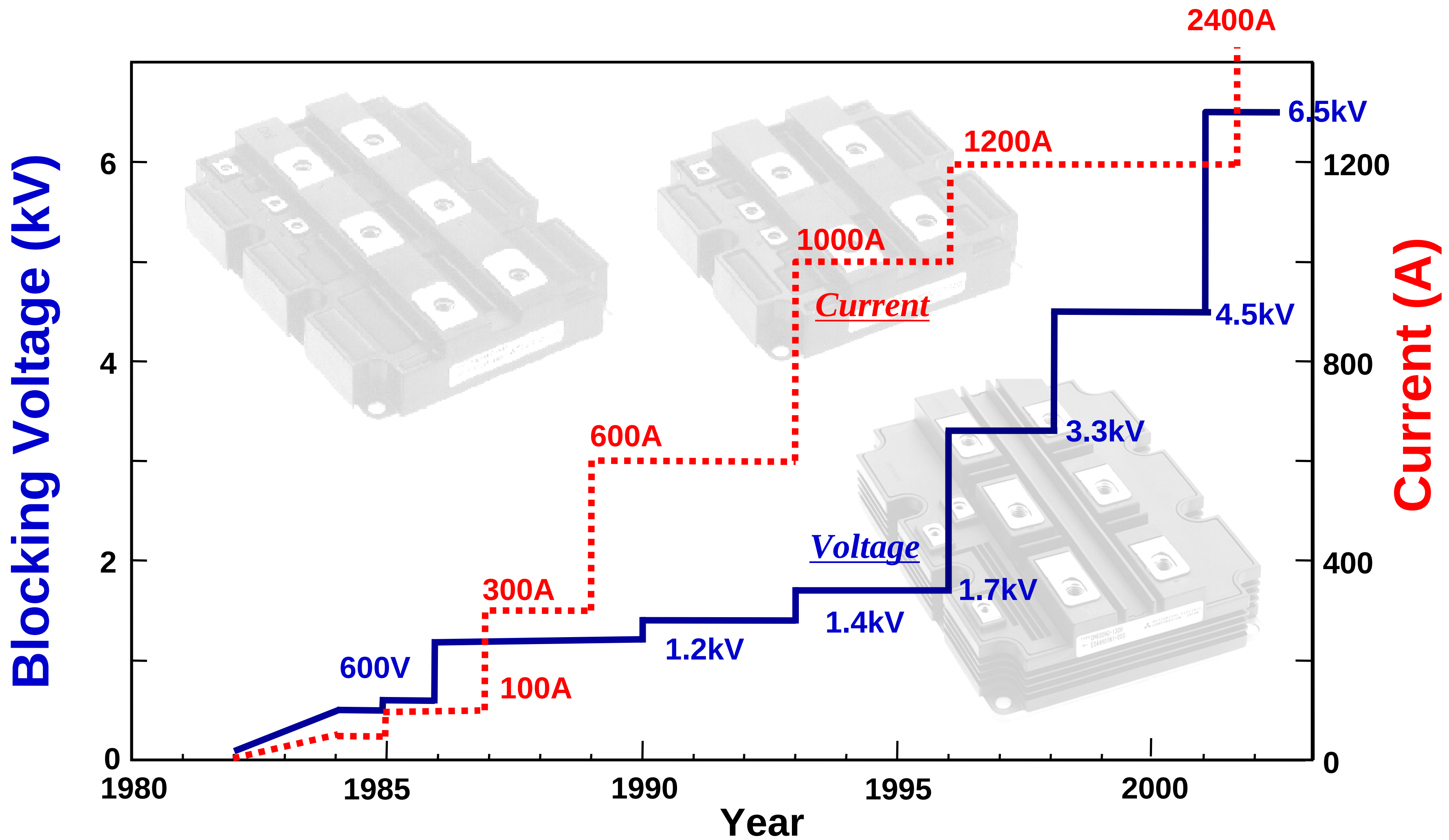




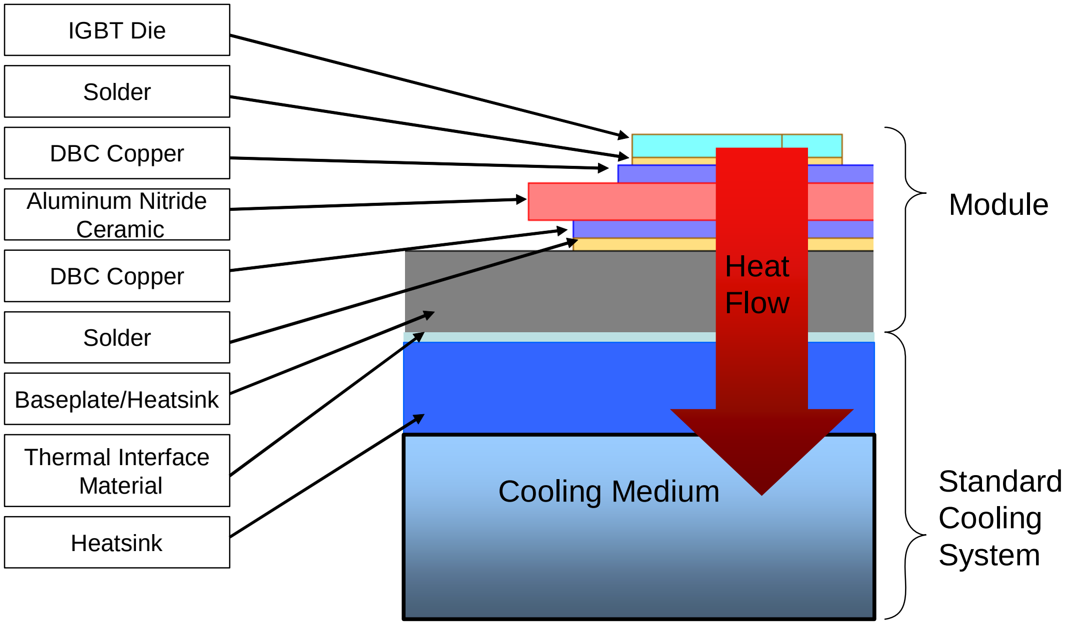
CPES
Center for Power Electronics Systems
A National Science Foundation Engineering Research Center

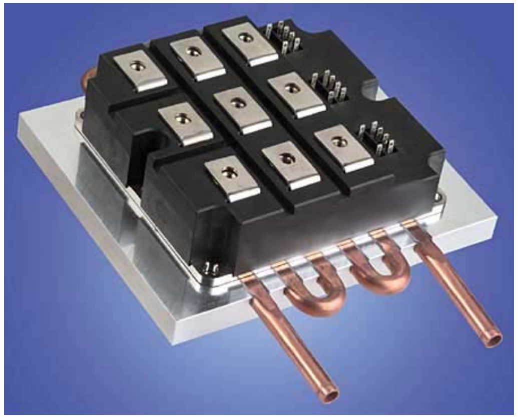


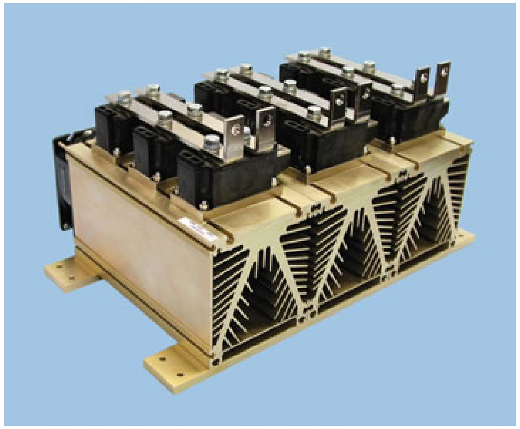
HV-IGBT Voltage Ratings Now Up to 6.5kV



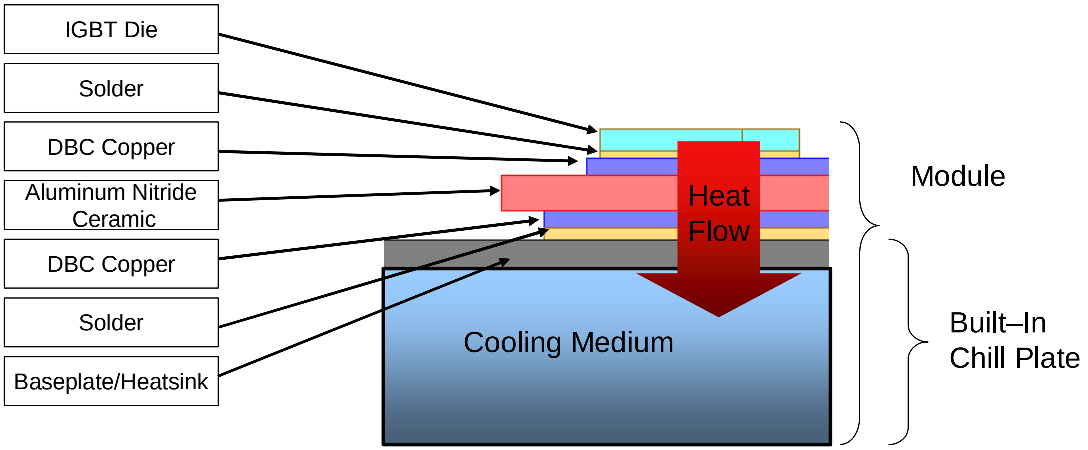
Standard Power Module Cooling



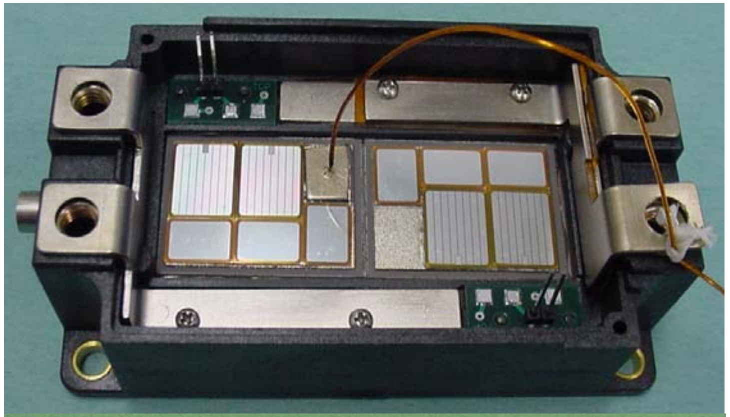


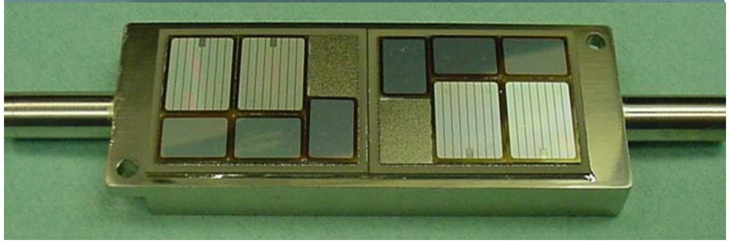


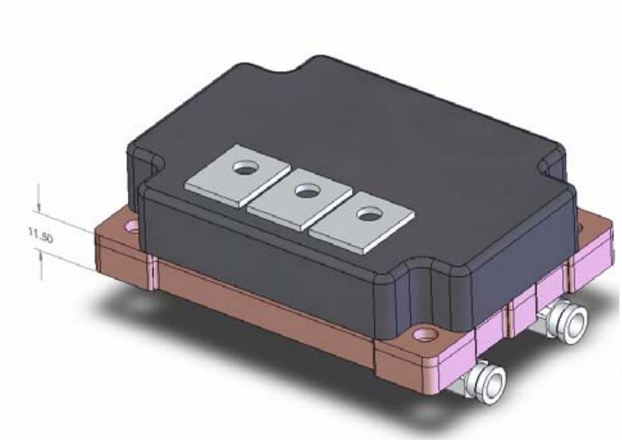
Modules with Built-In Heatsink – Reduced Heat Flow Path



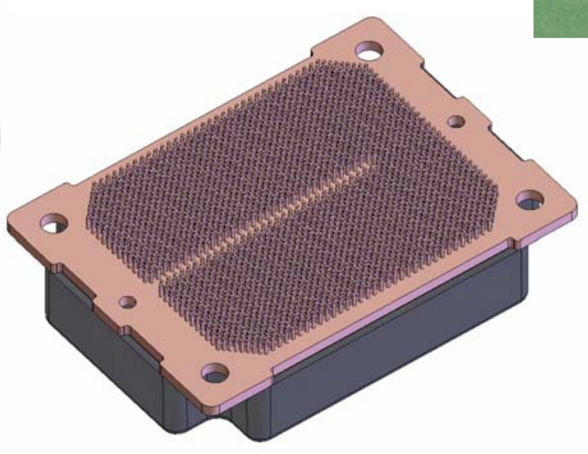
Normal Flow Microchannel Cold Plate



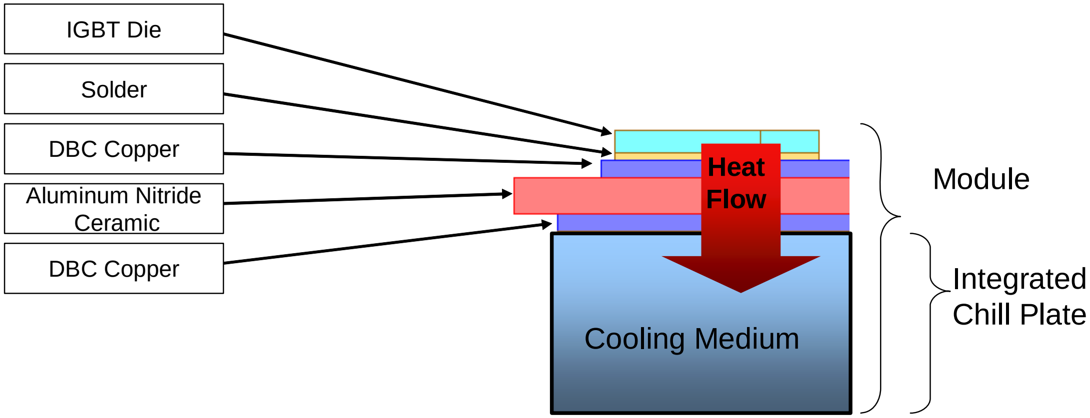




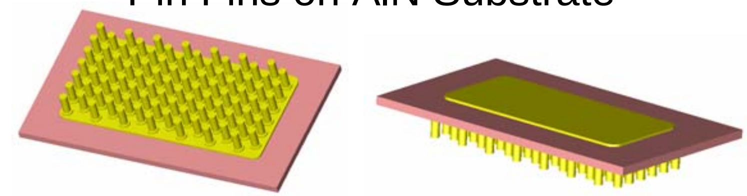
“Pin Fin” Baseplate

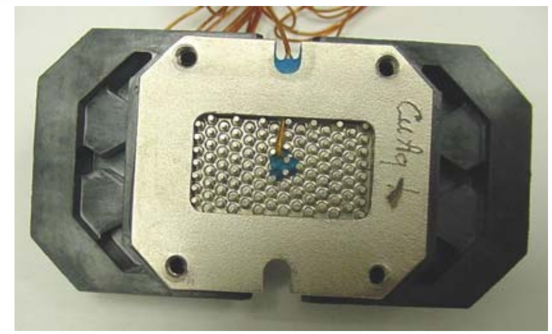


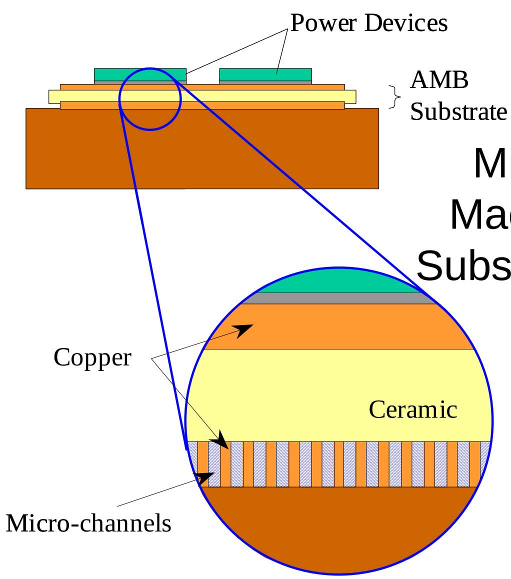
Modules with Integrated Heatsink – Reduced Heat Flow Path



Pin Fins on AlN Substrate

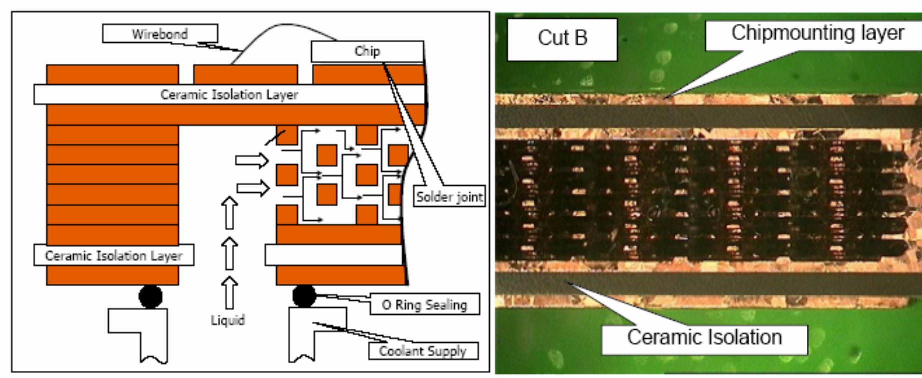




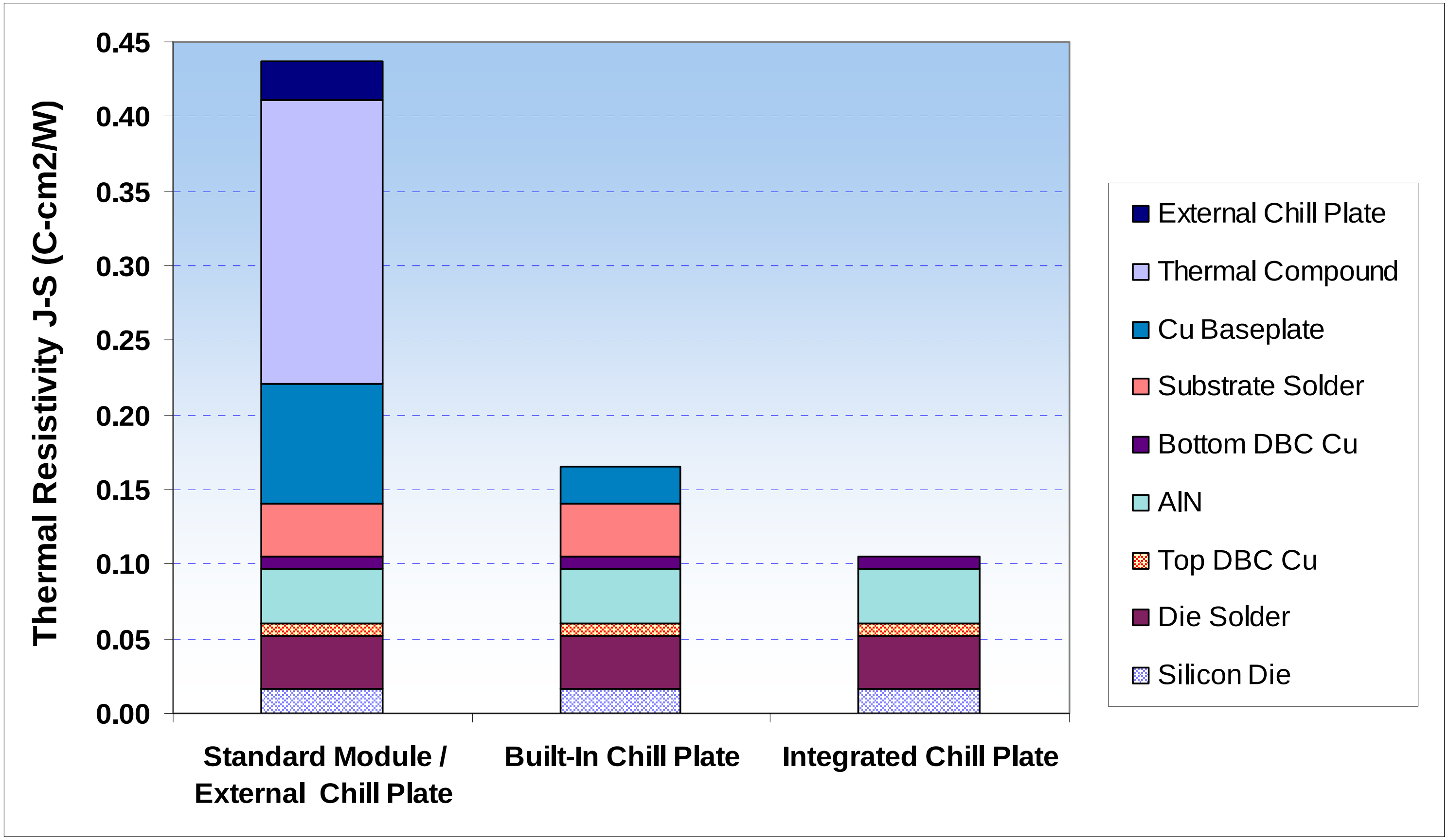


Microchannels Machined in AlN Substrate (GECRD)

AlN/Cu Substrate Micro Channel Cooler (Curamik)

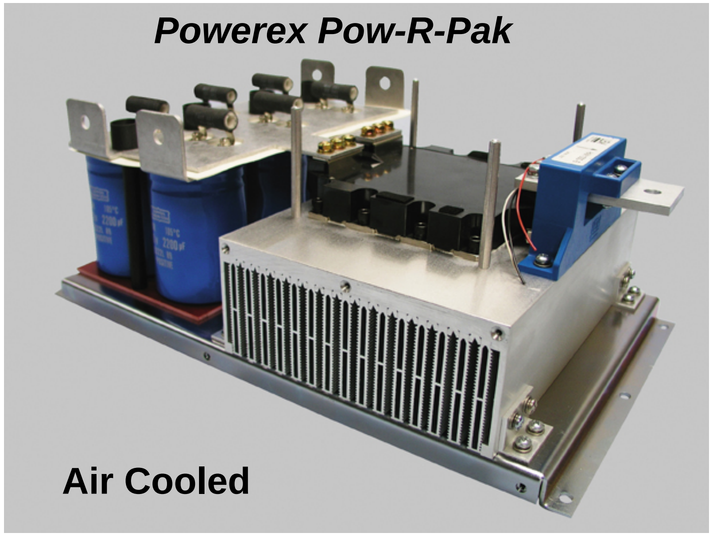


Thermal Resistivity Comparison of Paths to Cooling Medium

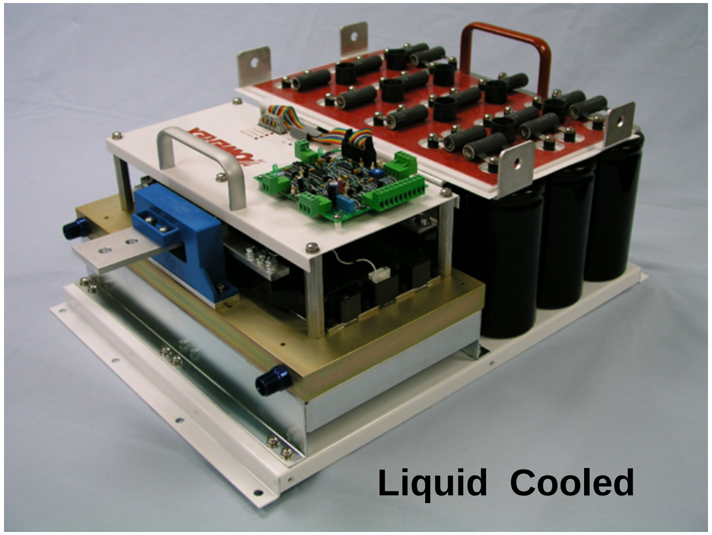


Assembly Subsystems – Beyond Systems in a Module

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

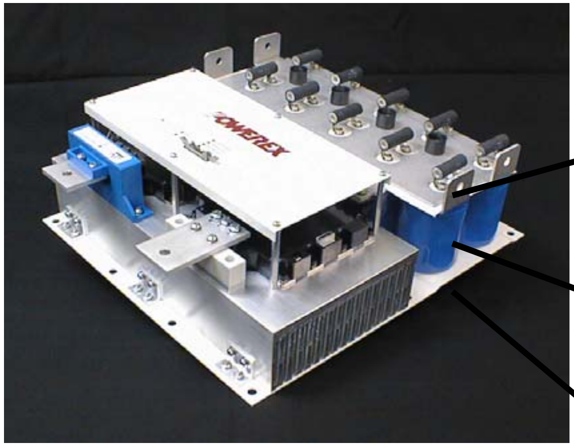


Semikron Skiip Pack

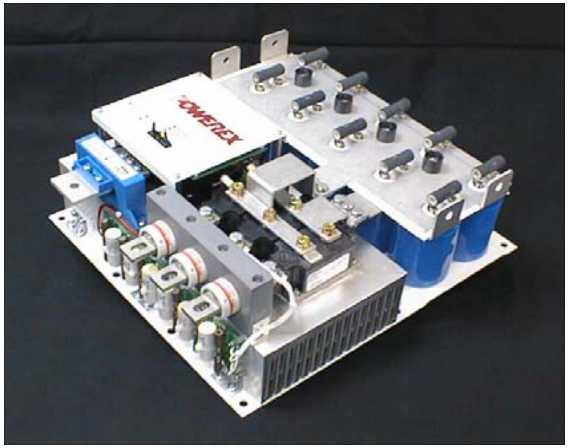


System Integration

Motor Leg Inverter



Converter & Brake Chopper



Power Module Packaging & Integration

Scott Leslie
Chief Technologist

John Donlon
Applications Engineer

Session 4b

Reass II

MULTI-MEGAWATT HIGH FREQUENCY POLYPHASE NANOCRYSTALLINE TRANSFORMERS*

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Jan 2007

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Abstract

High frequency power transformer designs now provide a viable method to significantly reduce the physical size, weight, and footprint as compared to conventional 60 Hz power transformers. In addition, recent developments in transformer core materials also give the ability to operate at high flux densities (> 1T) with excellent efficiencies. These authors prefer amorphous nanocrystalline alloy that provides the highest flux swing and lowest loss in the 20 kHz frequency range. The amorphous nanocrystalline alloy is a glassy amorphous spin-cast material available in ribbon tapes from various vendors. The tapes are then wound into the desired shapes and then processed to achieve the nanocrystalline structure. A cut-core design gives a simple transformer fabrication and assembly topology without a significant loss of electrical performance. Further optimizations can improve efficiency and/or size, depending on the specific application or requirement.

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
- <u>450 LBS for 3</u>
- 3 KW Loss At 2 MW
- "C" Core Design (Parallel Windings)

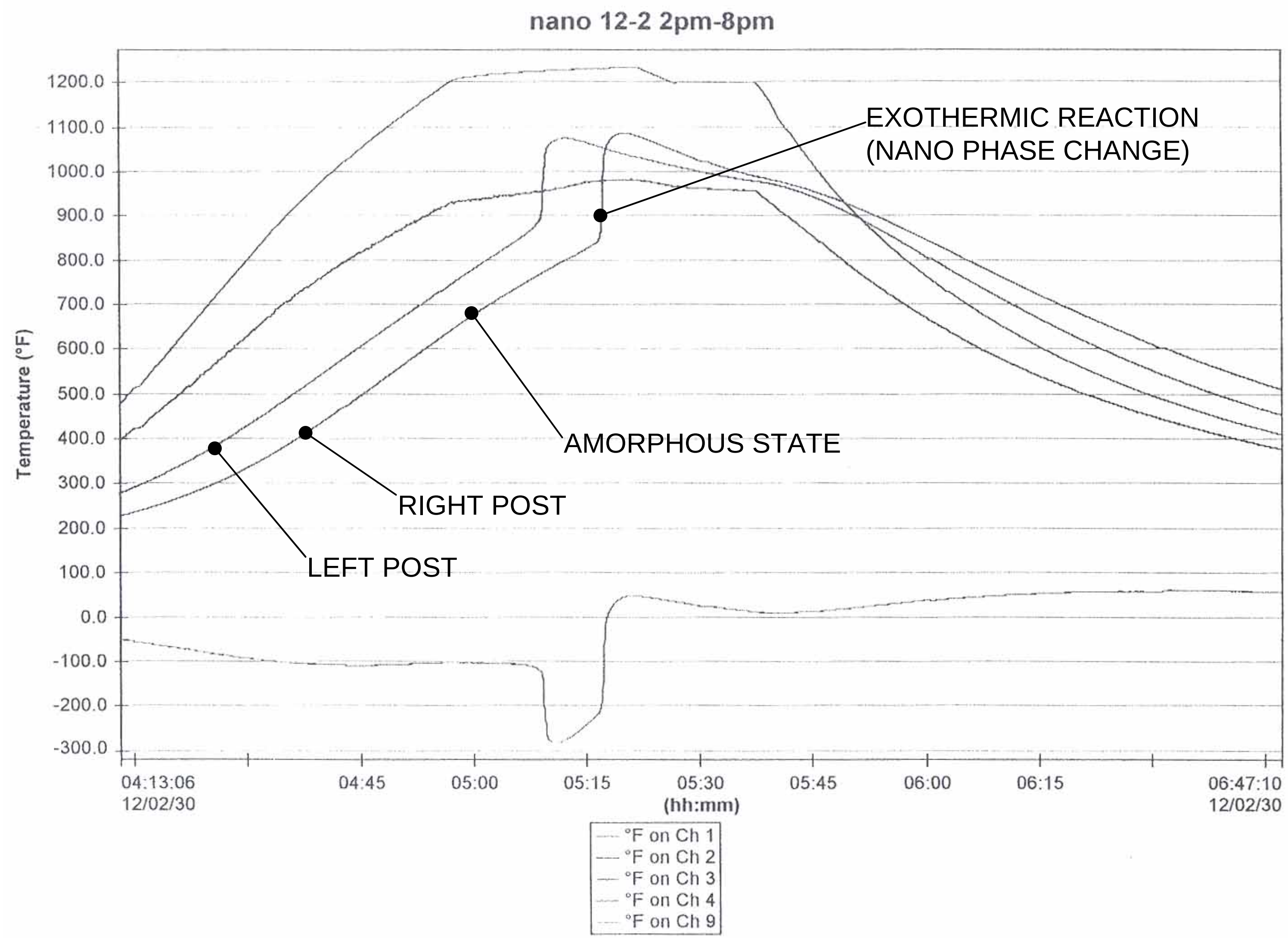
Typical H.V. Transformers

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

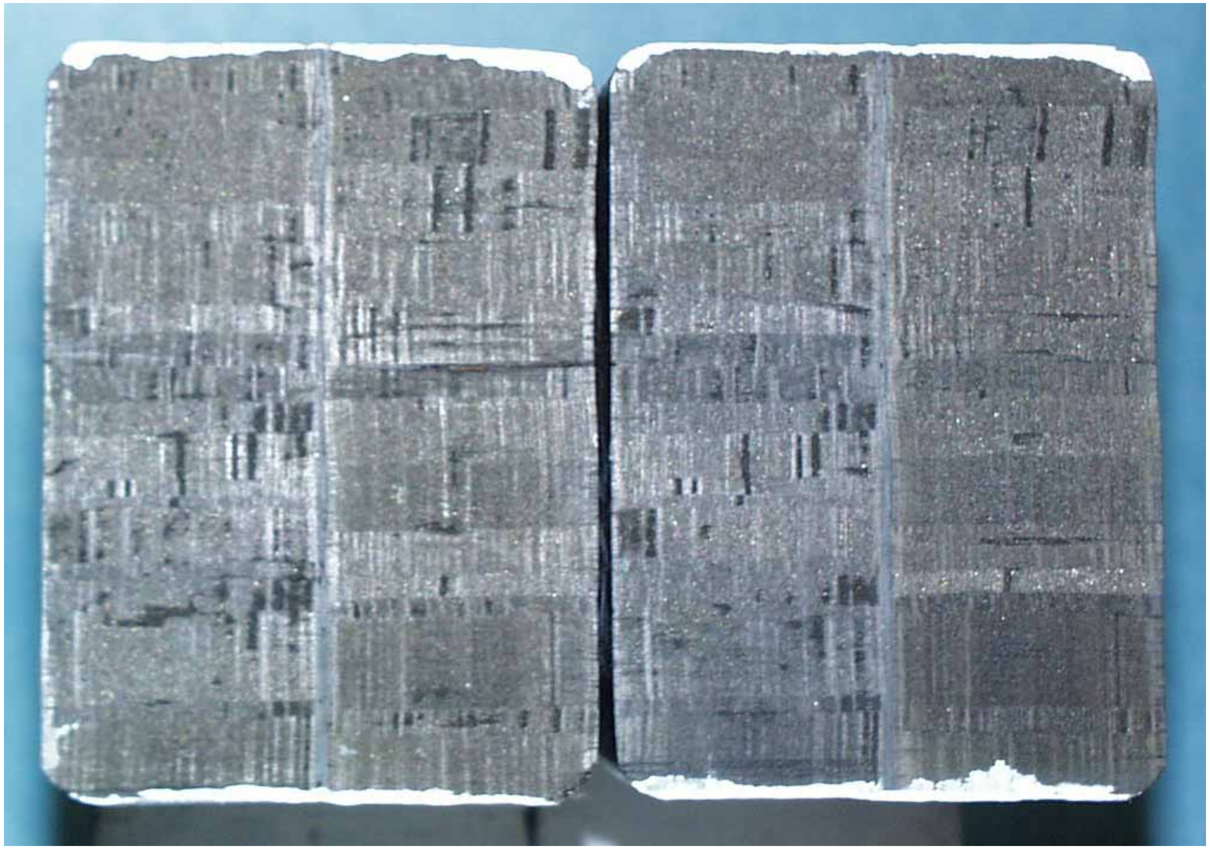
Nanocrystalline Transformer Development

- Funding Provided To Develop Manufacturing Processes
- Winding (Nano Shrinks ~1% During Processing)
  - Loose
  - Compressible Mandrel
- Process Regulation (Exothermic Reaction)
  - Temperature Control – Feedback Controlled Oven Temperature
- 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 Core Phase Change



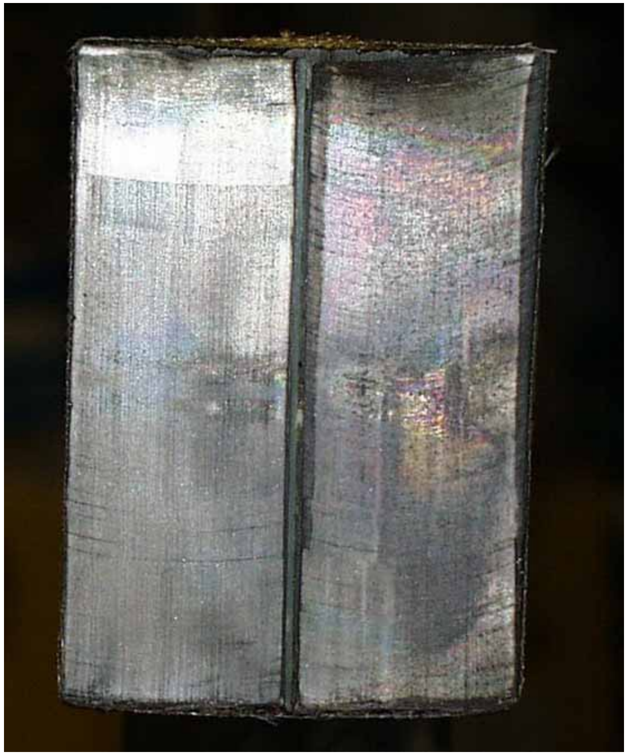
Russian EDM Cut Nano Core



- Not A Good Process
- Significant Pole Face Pitting

VacuumSchmelze Cores

- Loose Lay-Up
- Poor Dimensional Characteristics
- Low Stacking Factor
- Wet Lay-Up
- Fiberglass Tape For Mechanical Strength



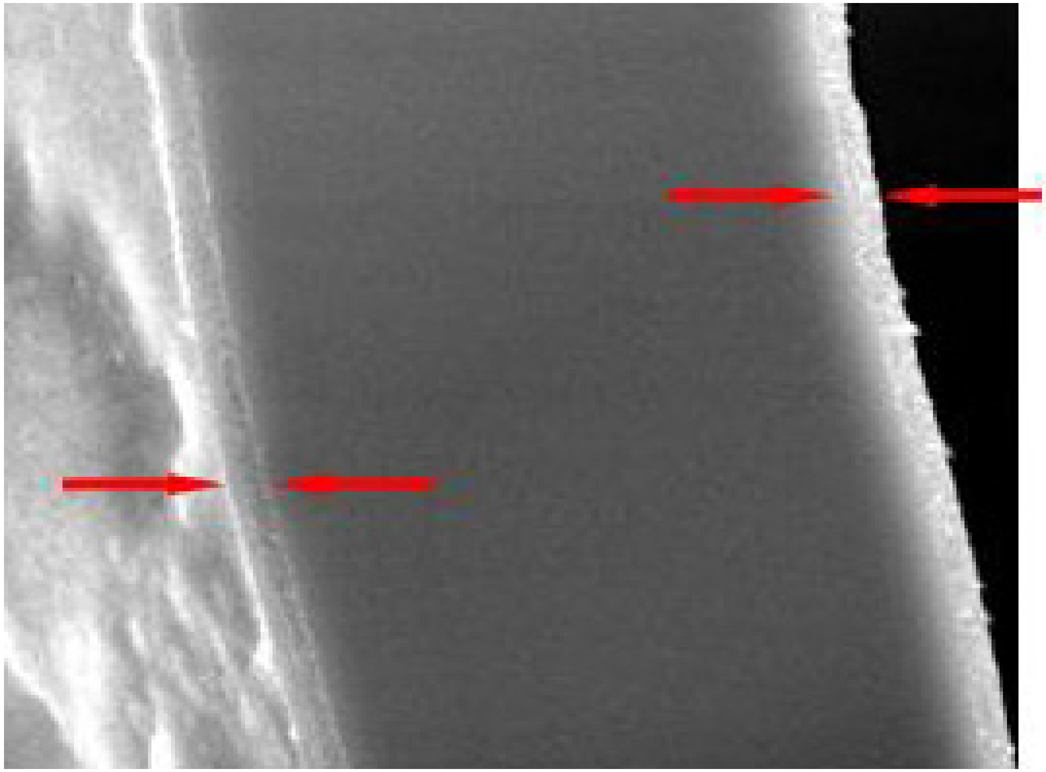
- Poor Adhesion
- Lamination Cupping
- No Pole Face Etching
  - Lower Pole Face Resistance

Nanocrystalline Transformer Development Results

Nano Material Characteristics

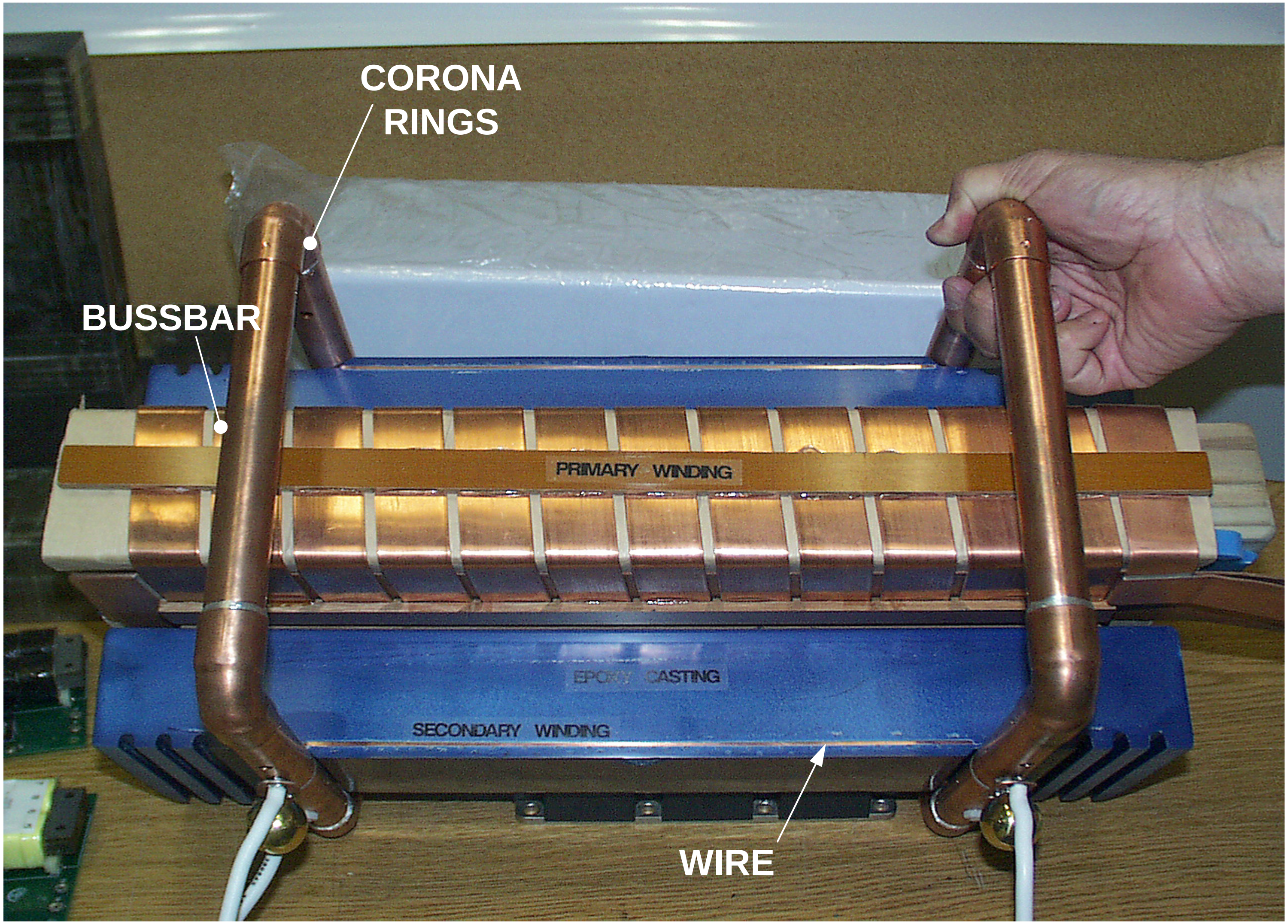
Mu	50,000
Lamination Thickness	.0007"
Lamination Insulation	<1 µM
Stacking Factor	~90%
Bsat	12.3 kG
Core Loss (our use)	~300 W
Core Weight (our use)	~95 lbs
Power (each core)	330 kW

Oxide Insulating Coating



- Near Zero Magnetostriction
  - No Significant Core Vibration Or Noise

Boost Transformer Winding Design (140 kV)



Recent Developments

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

Advanced Transformer Geometry

- Polyphase Y
- Ring And Bar
- Triangle And Bar

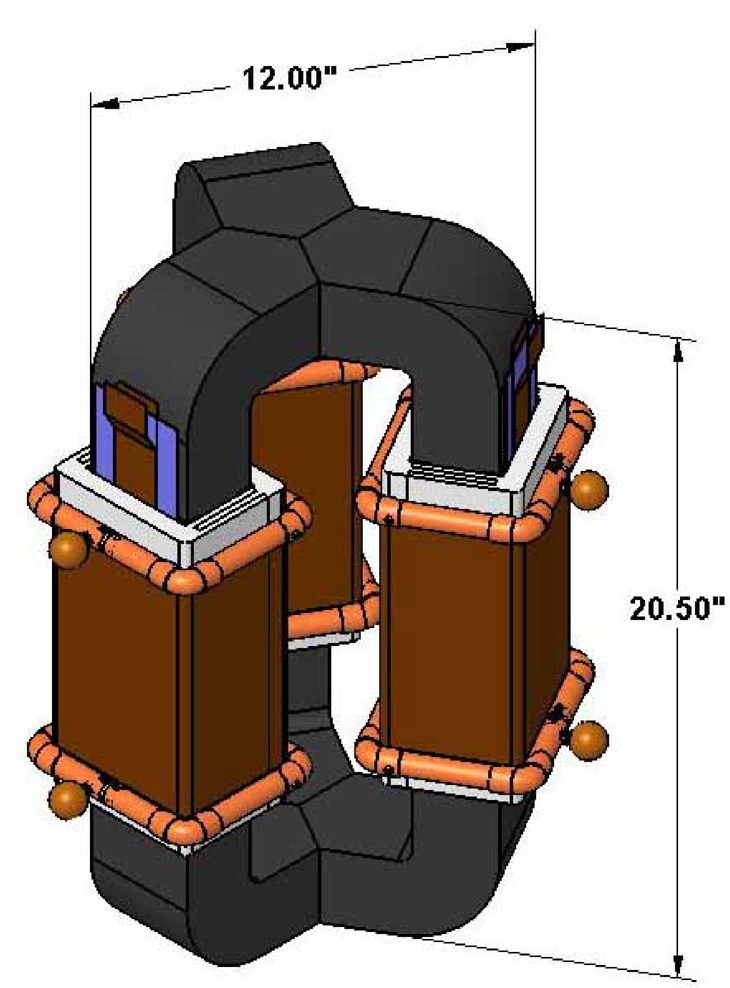
Polyphase Y

ADVANTAGES

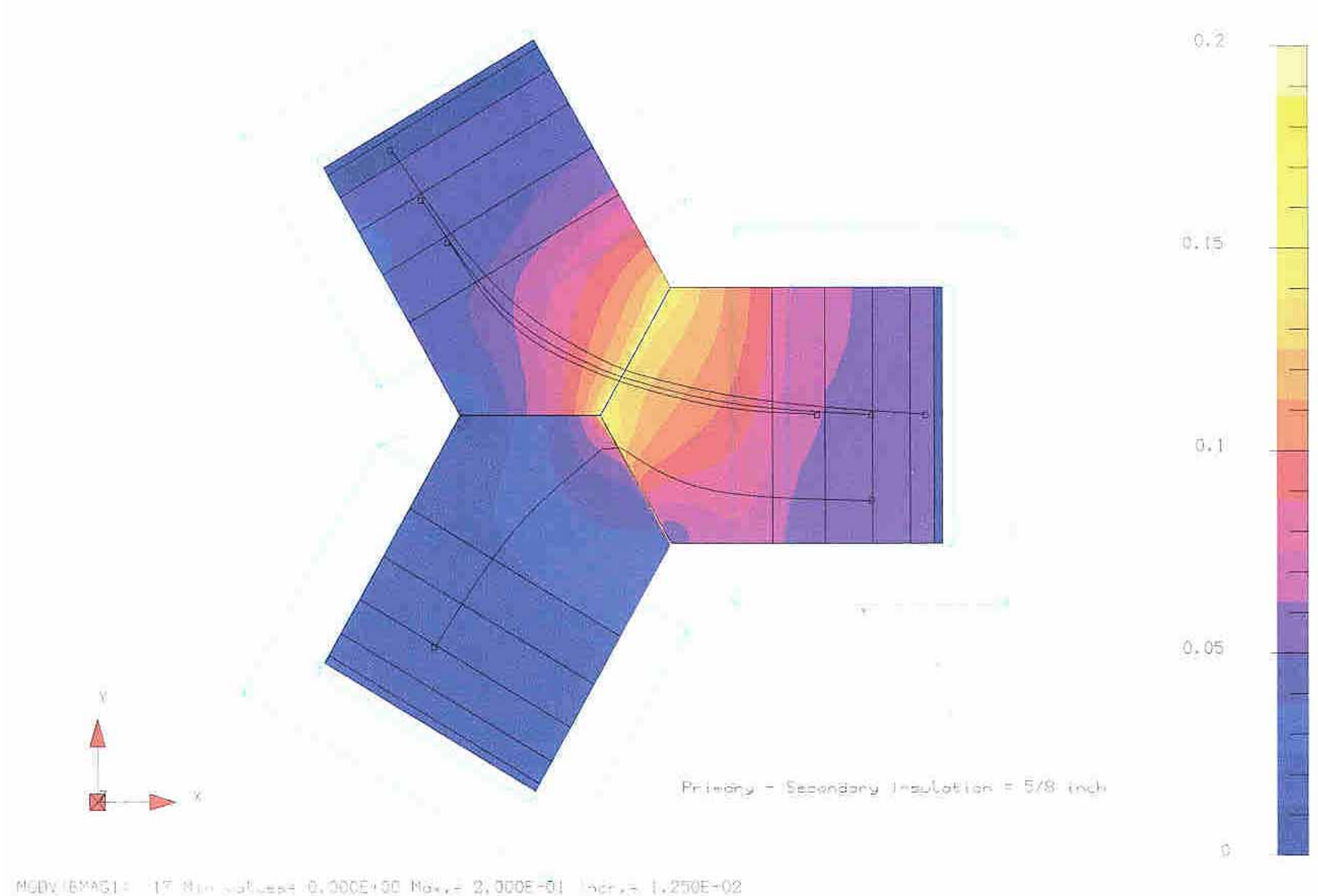
- Good Flux Balance
- Highest Performance
- 2 Gaps Per Winding Pair

DISADVANTAGES

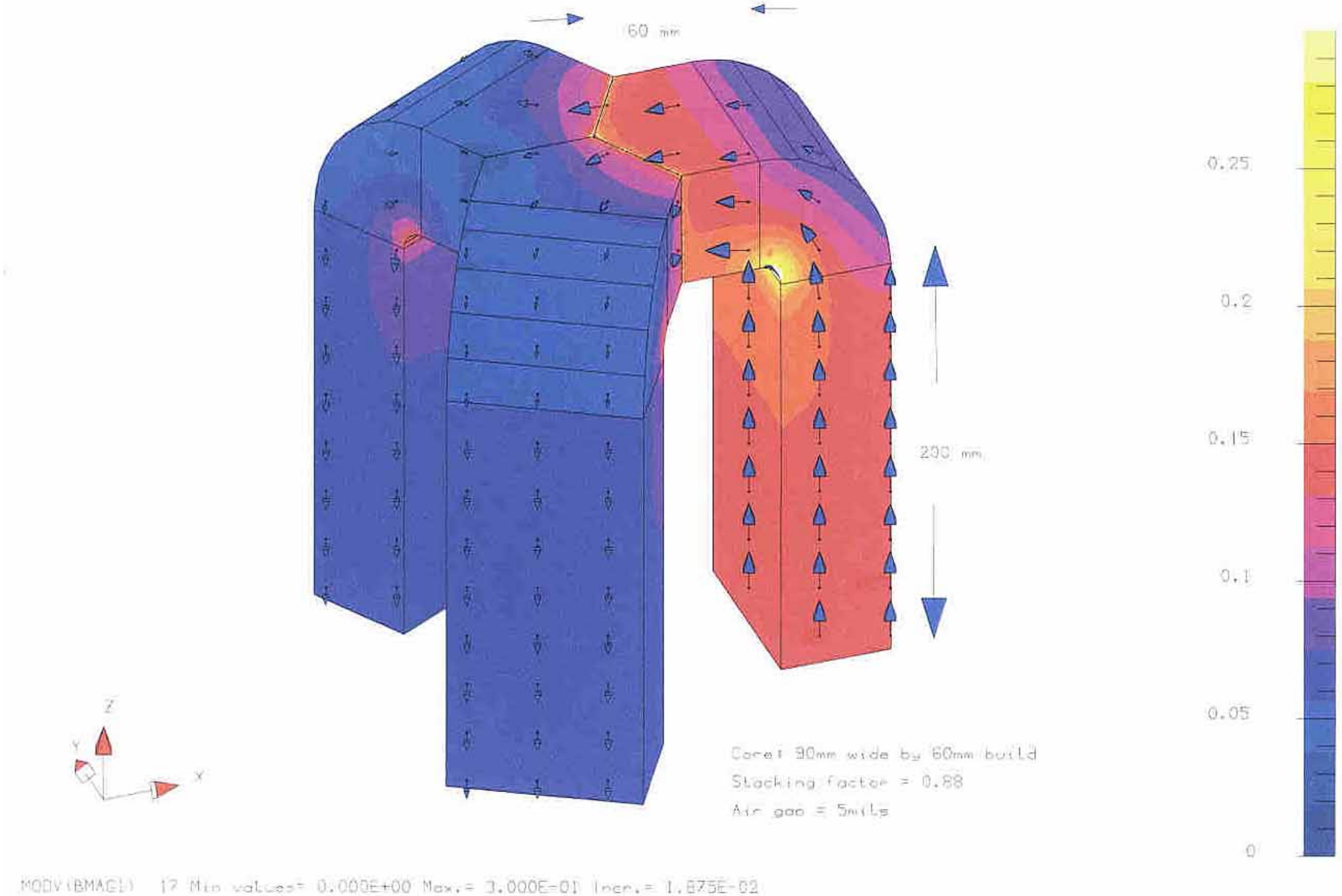
- Windings On Core
- Hard To Manufacture
- Sensitive To Tolerances
- Could Not Manufacture Previously



Flux Asymmetry Caused By Chamfer



Flux Concentration On Inner ID



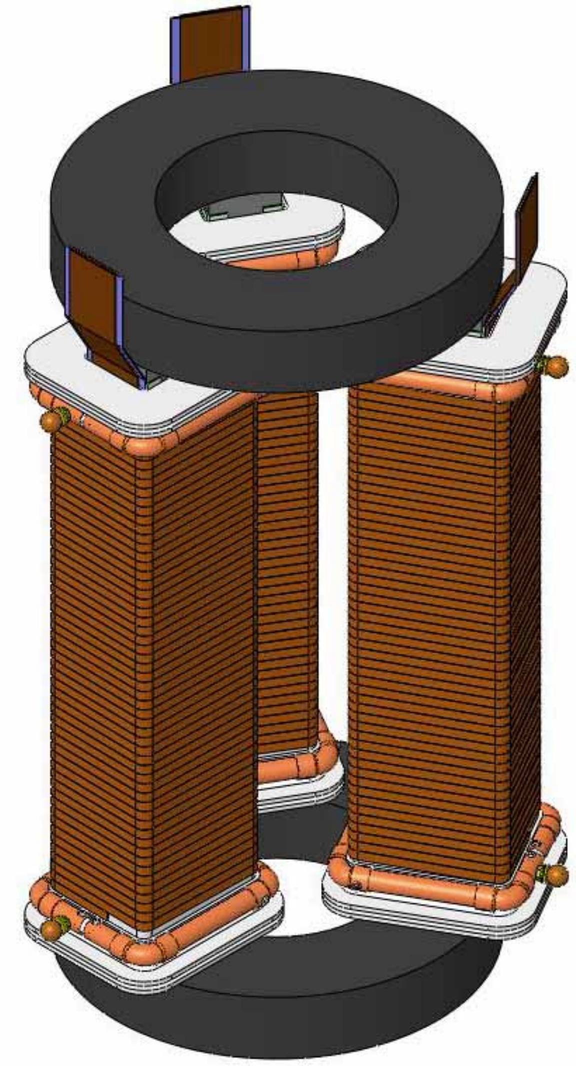
Ring Bar Transformer

ADVANTAGES

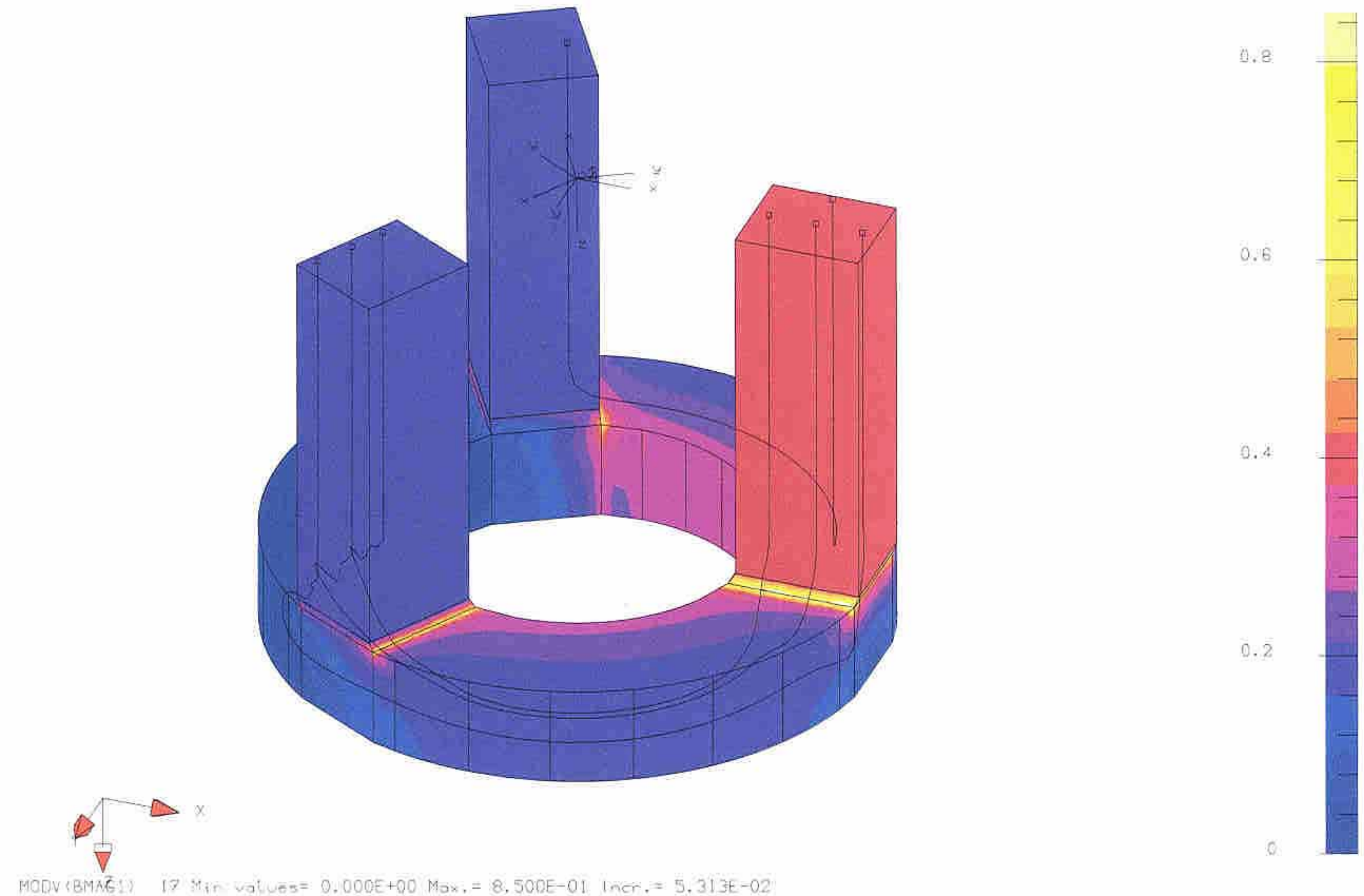
- Simple Topology
- Can Use Winding Bobbins

DISADVANTAGES

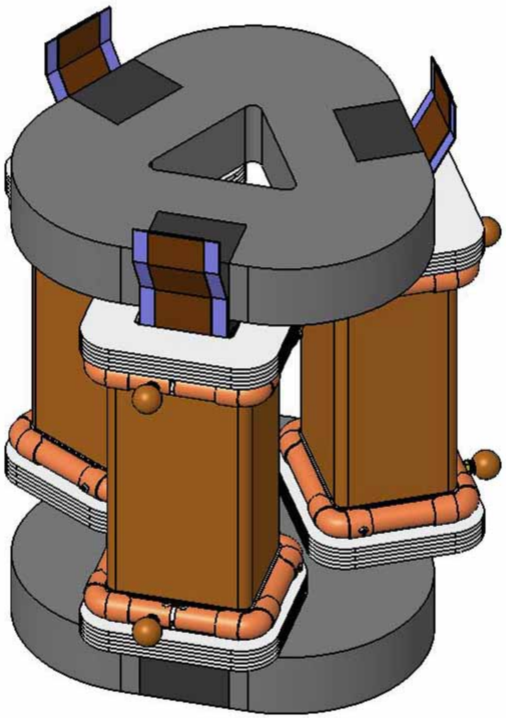
- Higher Reluctance Path
- 2X Core Gaps
- Mechanical Robustness (?)
- Secondary Tabs On Narrow Dimension



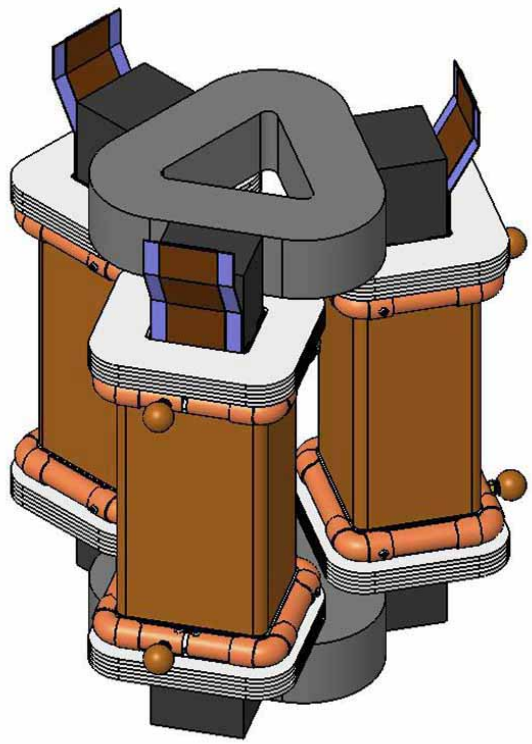
Some Flux Concentration At Interface



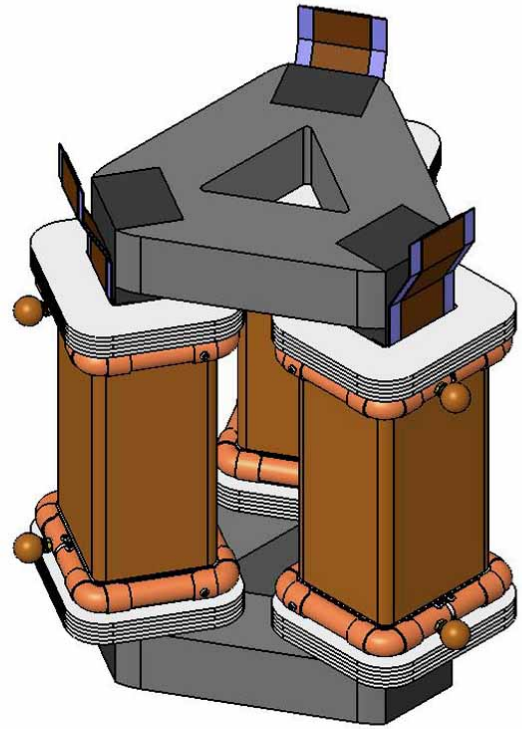
Triangular Bar Transformer Design Possibilities



OPTION 1



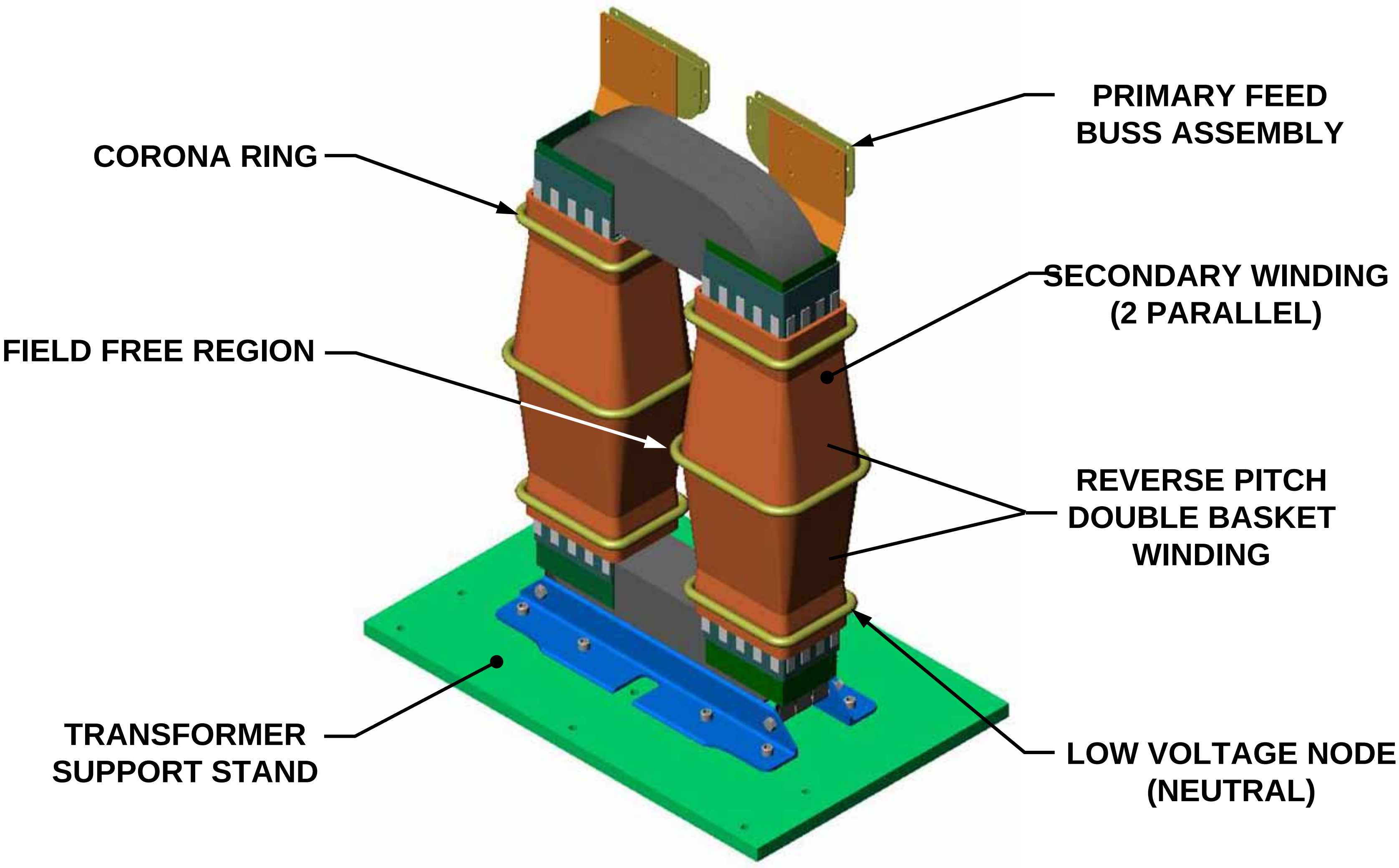
OPTION 2



OPTION 3

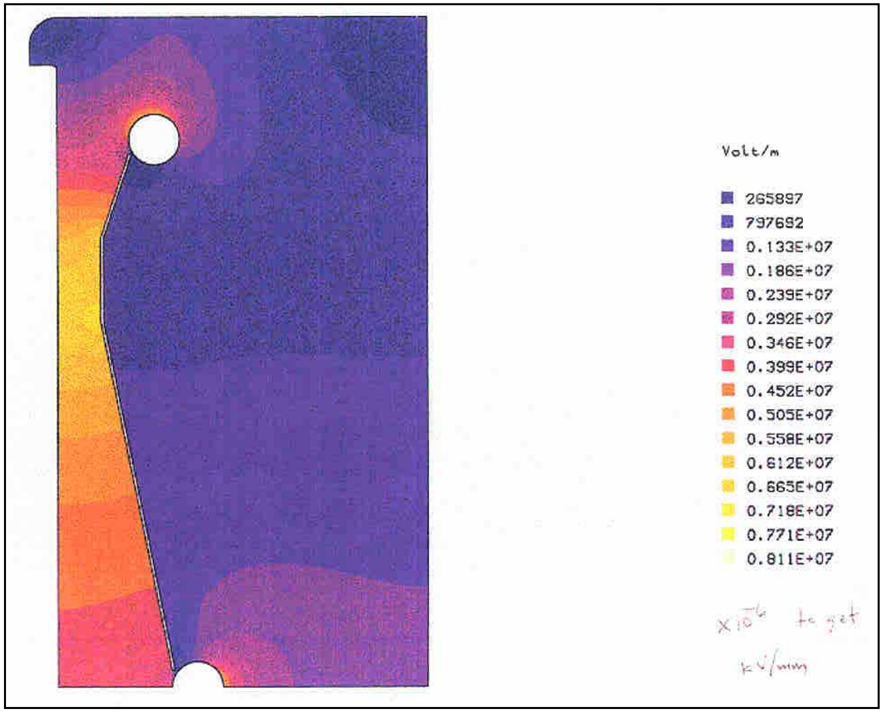
Flux Concentration At Corner And Interface

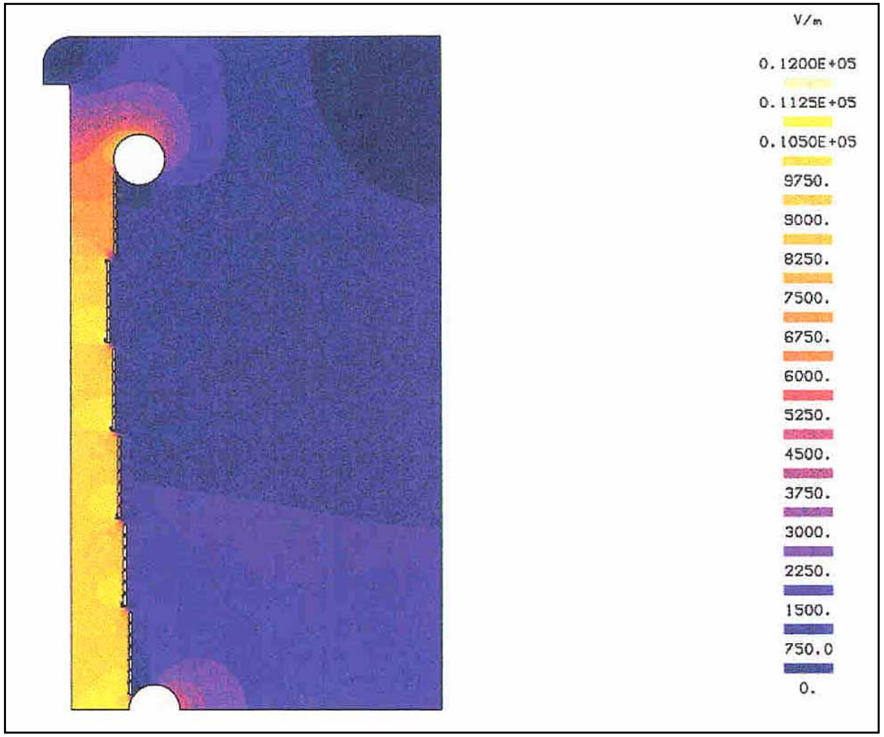
C-Core Designs Offer Higher Efficiency



Advanced Winding Topology Minimizes Field Stresses And Leakage Inductance

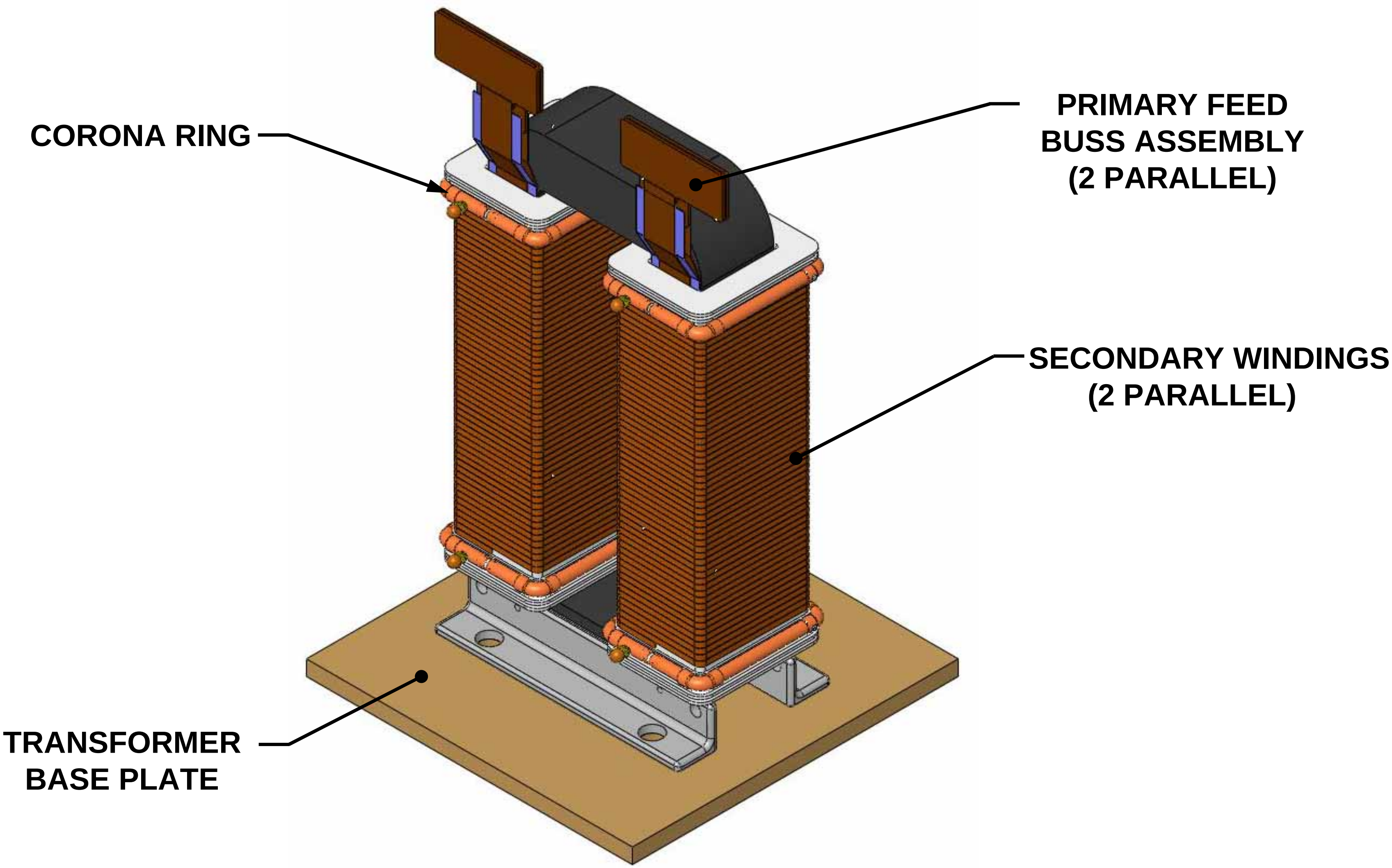
Winding Taper Improves Performance





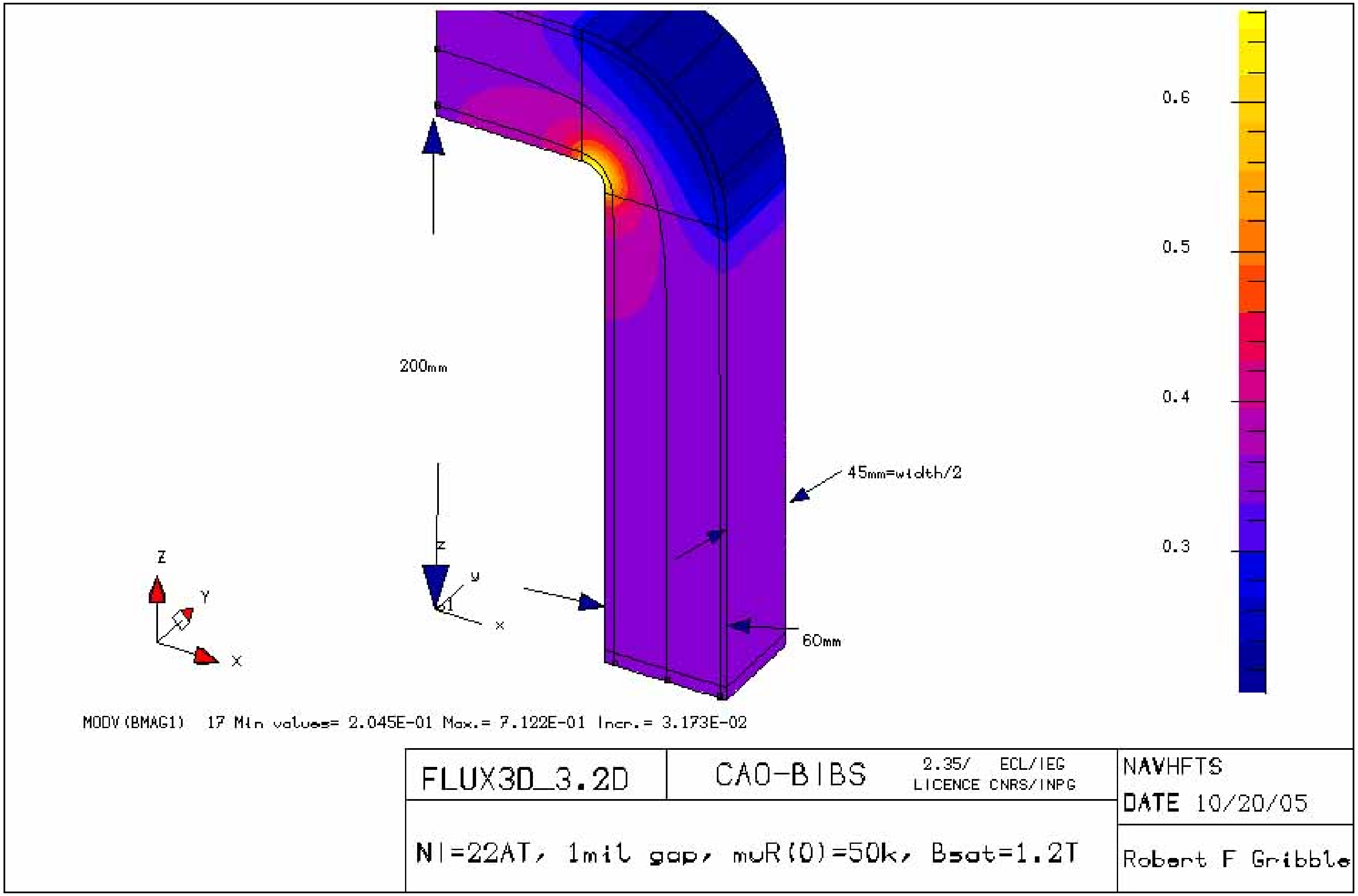
- Double Basket Design has Lower Field Stress
- Lower Leakage Inductance (than single layer solenoid with same field stress)
- Minimized End Effects
- Hard to Wind
- Reduced Copper Strength

A Simple C-Core Design



Use for Each Phase of Multiphase System

“C-Core” Flux Density



Transformer Conclusions

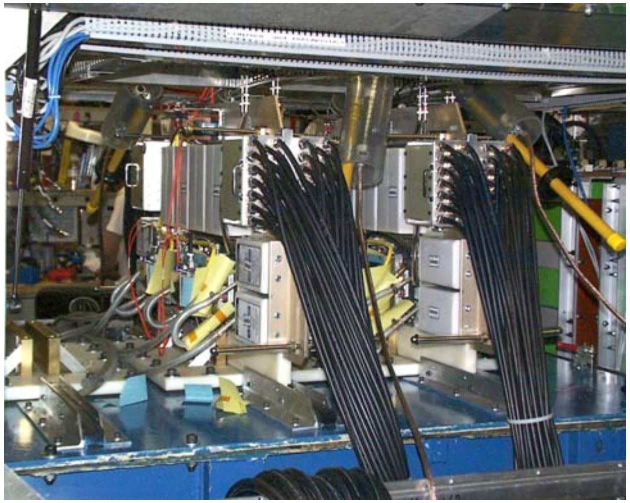
- C-core designs probably best for multiphase (more than 3) systems
  - Can drop single phase to continue operation

- Advanced core designs probably best for demanding requirements at mid-power levels using a 3 phase converter topologies

- Winding techniques are also important
  - Reduce leakage inductance
  - Reduce field stresses

What We Should Also Accomplish

20 KHz, 10 MW Polyphase Pulsed Converter



20 KHz IGBT Switching Assemblies

- We Can Reconfigure Los Alamos 10 MW, 20 KHz Pulse Converter To Evaluate Transformers
  - Appropriate Utilities In Facility For Full Power Testing
- We Can Use Facility To Test Critical Components And Performance
- Converter Can Be Upgraded To 2.7 MW CW (Now > 1 MW CW)
- Use Facility To Test Designs
  - Catalog Performances
- Facility Is Unique

Conclusion

Los Alamos Has Delivered Multi-Megawatt Class High Frequency Converter And Transformer Systems To Multiple Institutions. We look Forward To Teaming And Assisting The Further Development Of This And Related Technologies.

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Session 4b

Staines II

High-Megawatt Converter Technology Workshop

Capacitor Technology for High-Megawatt Power Conversion

Dr Geoff Staines

General Atomics – Electronic Systems Inc

24 Jan, 2007

Film Capacitors for Power Conversion

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

IGBT switch plate assembly (LANL SNS modulator)

GA-ESI Research Objectives

- Long DC life at high energy density
- High-temperature Polymers
- Novel construction technique for high current and high energy density
- Improved metallized electrodes for self-healing and low ESR
- Packaging for high temperature and thermal management
- Thin film winding for low voltage applications

High Temperature Polymers

- **Polypropylene film capacitors have highest energy density at low temperature**
- **Performance degrades rapidly above 40°C**
- **Investigating high-temperature films including**
  - Polyphenyl sulfide (PPS)
  - Polyetheretherketone (PEEK)
  - Polyetherketoneketone (PEKK)

Improved Metallization

- Self-healing capacitors use thin metallization deposited on dielectric films instead of foil
- Fault current causes vaporization of metallized layer, quenching the fault discharge
- Thin (~300Å) metallization limits current and thermal dissipation
- Challenge is to improve thermal conductivity without sacrificing self-healing properties
- Self-healing allows operation up to limit of film breakdown voltage for higher energy density

Impact on Converter Costs

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

Summary

- **Depending on frequency, capacitors can be the largest components in power converters**
- **Future development to focus on**
  - Increasing energy density
  - Reducing loss
  - Improving thermal management
- **Significant improvements in fast capacitor technology expected from improved engineering using proven film technology**
- **Smaller passive components may reduce requirement for high switching speeds**

Session 5

Hefner II

Discussion of:

High Megawatt Fuel Cell Power Converter Technology Impacts Study

(NIST/DOE Interagency Agreement)

Allen Hefner

NIST

Needed:
Inputs from High MW Community

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

Consensus at High MW Meeting

- Specifications for filter requirements
  – Inverter Harmonics requirment: IEEE519
  – EMI requirements: Mil STD 461 or equivalent
- Specifications FC DC regulator
  – Ripple requirement:
    <3% for frequencies < 1kHz
- Year 2020 FC may be 2000 V (center-tap)

Session 6

Wolk

Roadmap Development

High Megawatt Converters for Commercial Scale Applications

Ron Wolk
High Megawatt Converter Workshop
January 24, 2007

Potential Markets

- DOE Applications
  - 250-800 MW SECA-Based IGFC FutureGen Power Plants (with CO2 capture)
  - Freedom Car
- HVDC Power Transmission
- DOD Applications
  - Pulsed power
  - Vehicle motive power
  - Ship power generation and distribution
  - Ship propulsion

Roadmap Development Issues

- 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?
- How should a Roadmap process to achieve this objective be organized?
- Should it work down from topologies (market pull) or up from materials (technology push)
- Should a continuous integration and evaluation process be used to identify the most promising targets of opportunity?

What's Next ?

- Formation of a committee to participate in developing the Roadmap
- Volunteers to staff the committee and its subcommittees
- Should subcommittees be organized by market thrust, product power capacity, time frame of development, other bases?
- Timeline for development of the Roadmap
- Would the formation of an Interagency Task Force on this subject be of value?

Contributed

Khersonsky

Yuri Khersonsky

Consultant

(Contributed but not presented at Workshop)

Navy Traditional Requirements for Megawatt Converters

3 R:

- Reliability
- Reparability
- Redundancy

3 S:

- Survivability
- Shock & Vibration
- Size & Weight

Numerical:

- 300% Overload
- <3% THD as a Load
- <1% THD as a Source

General:

- Noise Immunity
- Low EMI
- Parallelability

Fault Management Issues in Megawatt Converters

Fault Management Goals:

- Protection from Failed Components
- Elimination of Nuisance Trips
- Do not start the fire

Fault Management Strategy:

- Continuous Fault Monitoring
- Faults Detection with minimum delays
- Redundancy of Faults Detection
- Fault Isolation

Standardization objects

- **Power sizes (dimensions)**
- **Power Interfaces (connections)**
- **Signal Interfaces**
- **Communications protocols**
- **Protection and Fault management**
- **Safety requirements**

5 Rules of useful Standard

1. It does not regulate
2. It describes what need to be done and considered, not how it should be done
3. It establishes multiple sizes & interfaces levels (one size fits all does not work)
4. It formulates requirements based on collective experience and consensus
5. It leaves room for future enhancements

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