Power Electronics -- *Electrical Energy Conversion*
Machines & Power Electronic Building Blocks

3rd Annual Solid State Energy Conversion Alliance (SECA) Workshop

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Surface & Subsurface Platforms

Government Program Contacts

DoE

- Mr. David Hamilton, PNVG, David.Hamiliton@hq.doe.gov, 202-586-2314
- Mr. Alec Bulawka, Photo-voltaic programs, 202-586-5633

ONR 333, Compact Power Sources, Richard Carlin

ONR 334, Advanded Electric Power Systems

- Mr. Terry S. Ericsen
- Mr. Gary M. Jebsen
- Dr. George Campisi
- Ms. Elaine J. Martin
- Mr. Steven R. Satzberg

NRL, Power Electronics (components and materials)

- Dr. Fritz Kub, NRL 6813
- Karl Hobart, NRL 6813
- Robert Stahlbush, NRL 6813
- Nelson Saks, NRL 6813
- Vince Harris, NRL 6342
- Roy Rayne, NRL 6351

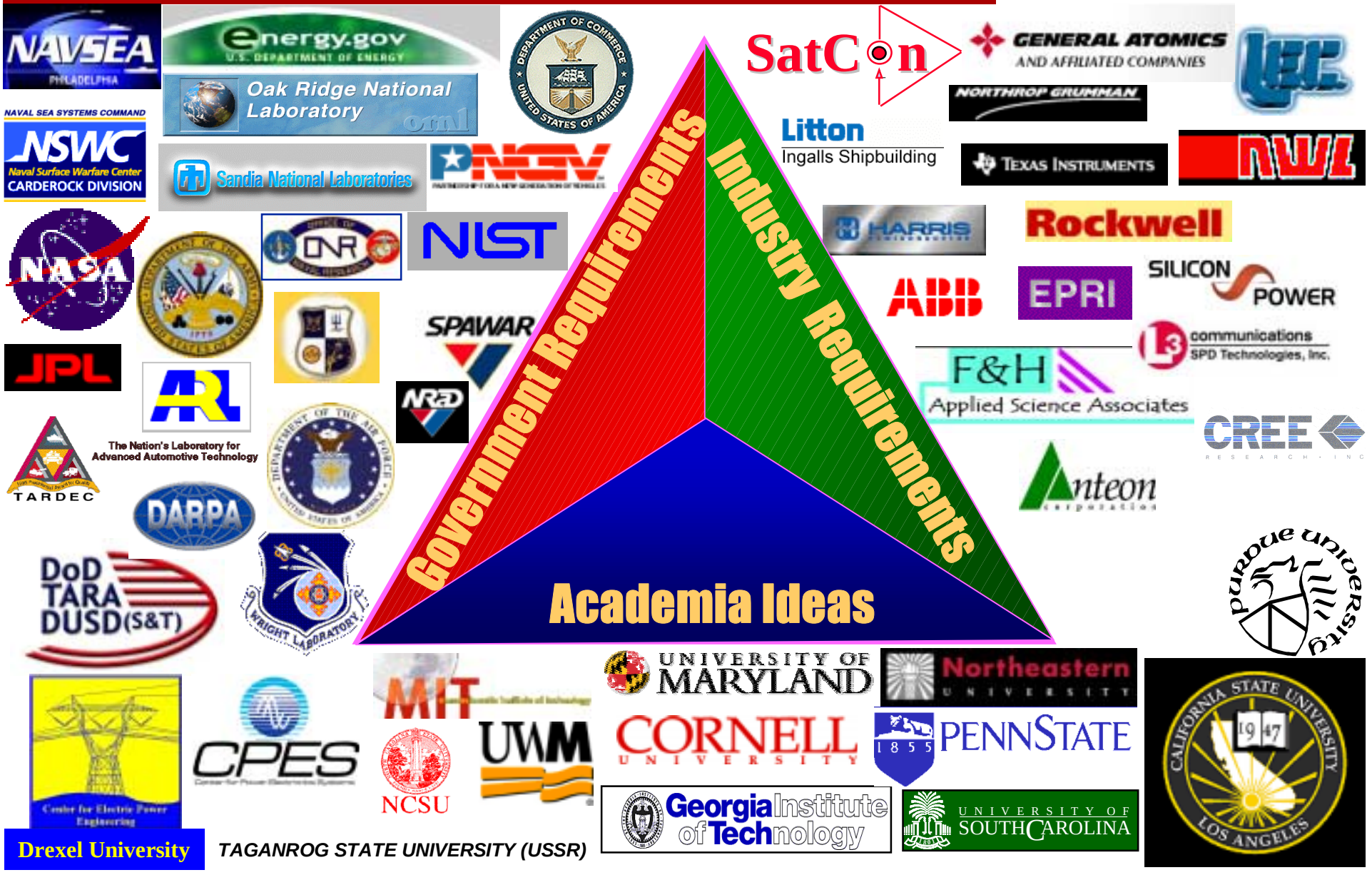
ONR 312 /DARPA, Wide BandGap Power Devices Thrust

- Dr. John Zolper, DARPA
- Dr. Ingham Mack, ONR 312
- Dr. Kristl Hathaway, ONR 312

Government–Industry–University Collaboration

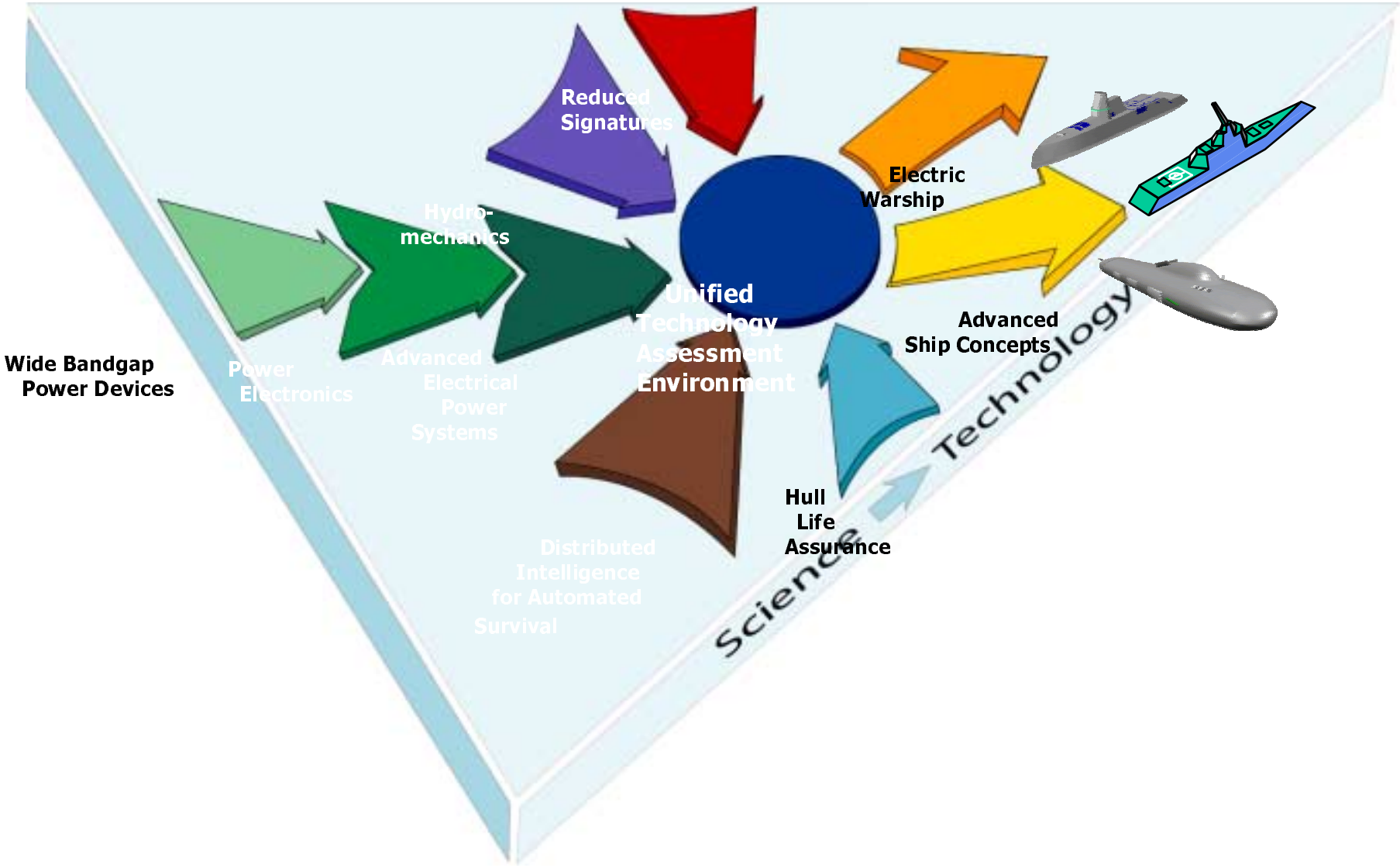
Surface & Subsurface

Diverse Participation Ensures Dual-Use Applicability



Surface & Subsurface Platforms

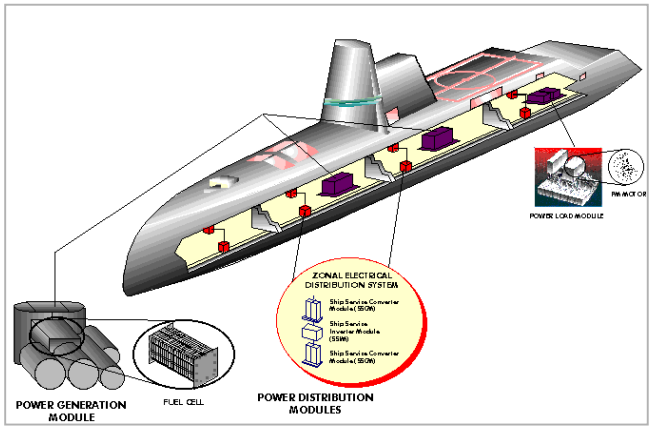
ONR Electrical Thrusts - Relationships



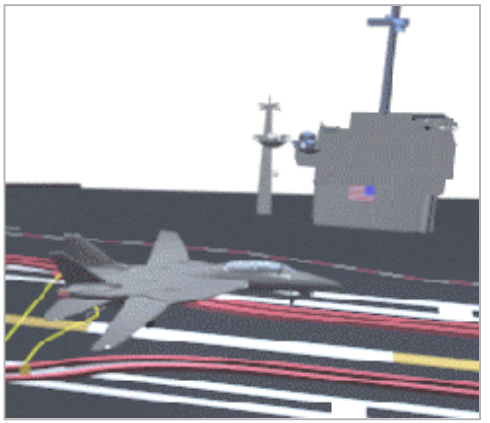
DoD Electric Power System Applications

Surface & Subsurface Platforms

Electric Warship

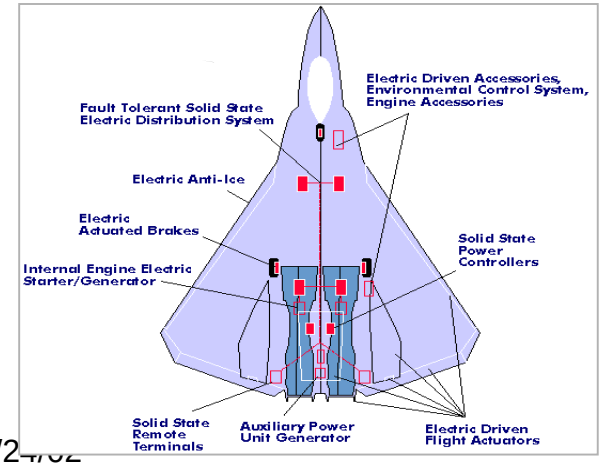


Electromagnetic Arrest and Launch



Pulse Power Weapons & High Power Sensors

More Electric Aircraft



Reconnaissance, Surveillance, Targeting Vehicle (RSTV)

Surface & Subsurface Platforms

Navy Systems Context

Relevance

- Increased survivability (Electric Warship)
- Reduced signatures (Electric Warship, Littoral ASW)
- Lower cost of stealth in future submarine designs. (TOC)
- Allow arrangement flexibility and electric power distribution for future weapons and payload enhancements. (Electric Warship, Littoral ASW)
- Need 10x reduction in size, and weight of shipboard electrical power system machinery (Electric Warship, Littoral ASW)

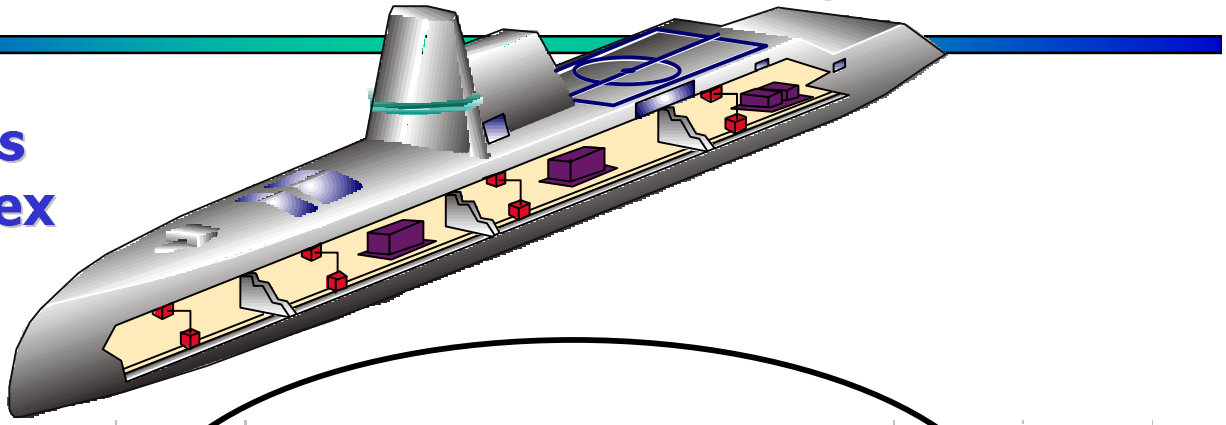
S&T Issues

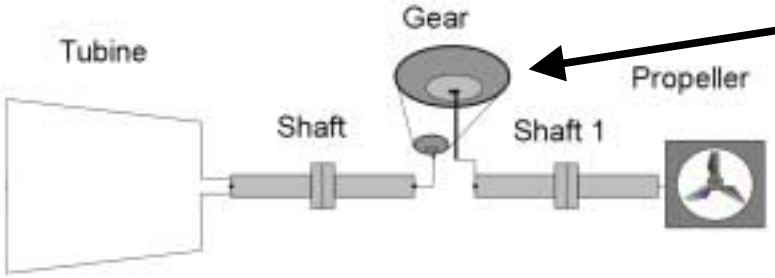
- Hierarchical & cellular design for Open Plug & Play Architecture
- Self-organization of systems of complex systems -- >10k State variables
- Simulation and control extending over >6 orders of magnitude in time
- Physics based analysis tools and models for non-linear circuits and loads and highly coupled power systems

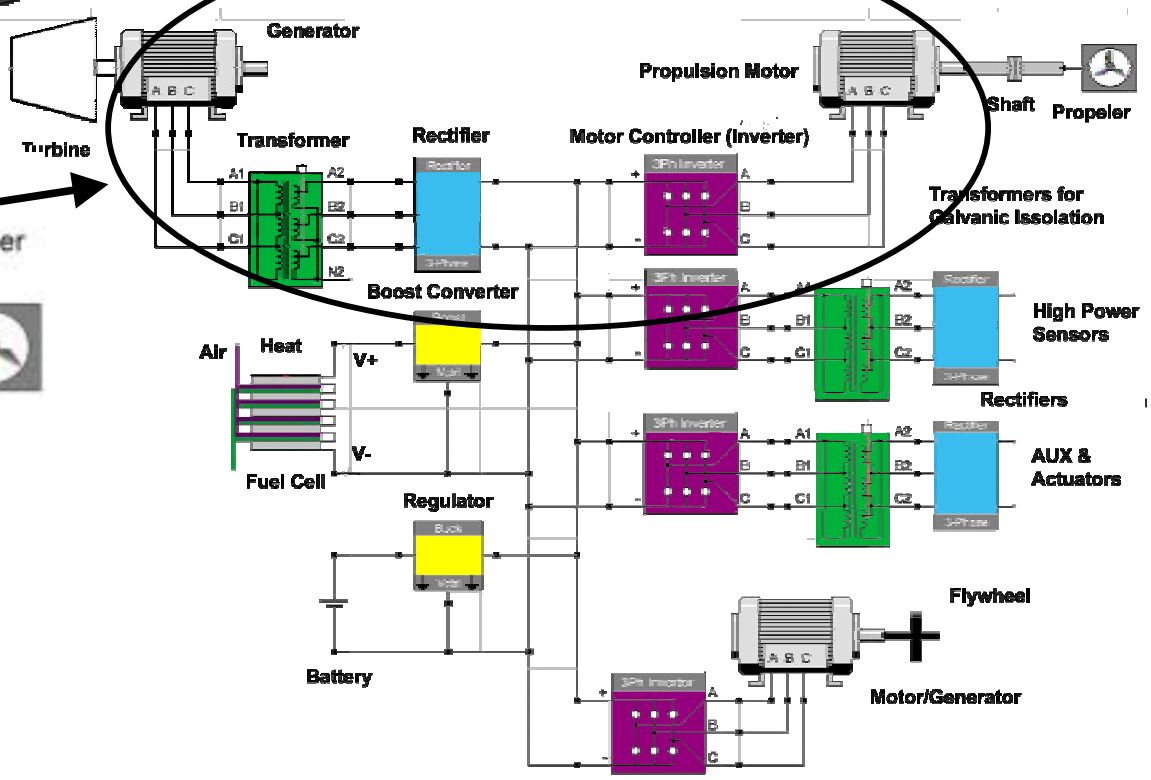
Advanced Electrical Power Systems

Surface & Subsurface Platforms

Electrical power systems are made of many complex energy conversion machines







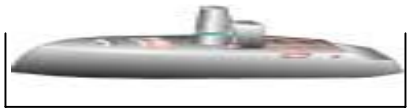
- ⇧ Power Density
- ⇧ Energy Density
- ⇧ System Efficiency
- ⇧ Control

A Mechanical Propulsion System Is A Shaft and A Set Of Gears

Surface & Subsurface Platforms

Future Electrical Power System Requirements

856 ft.



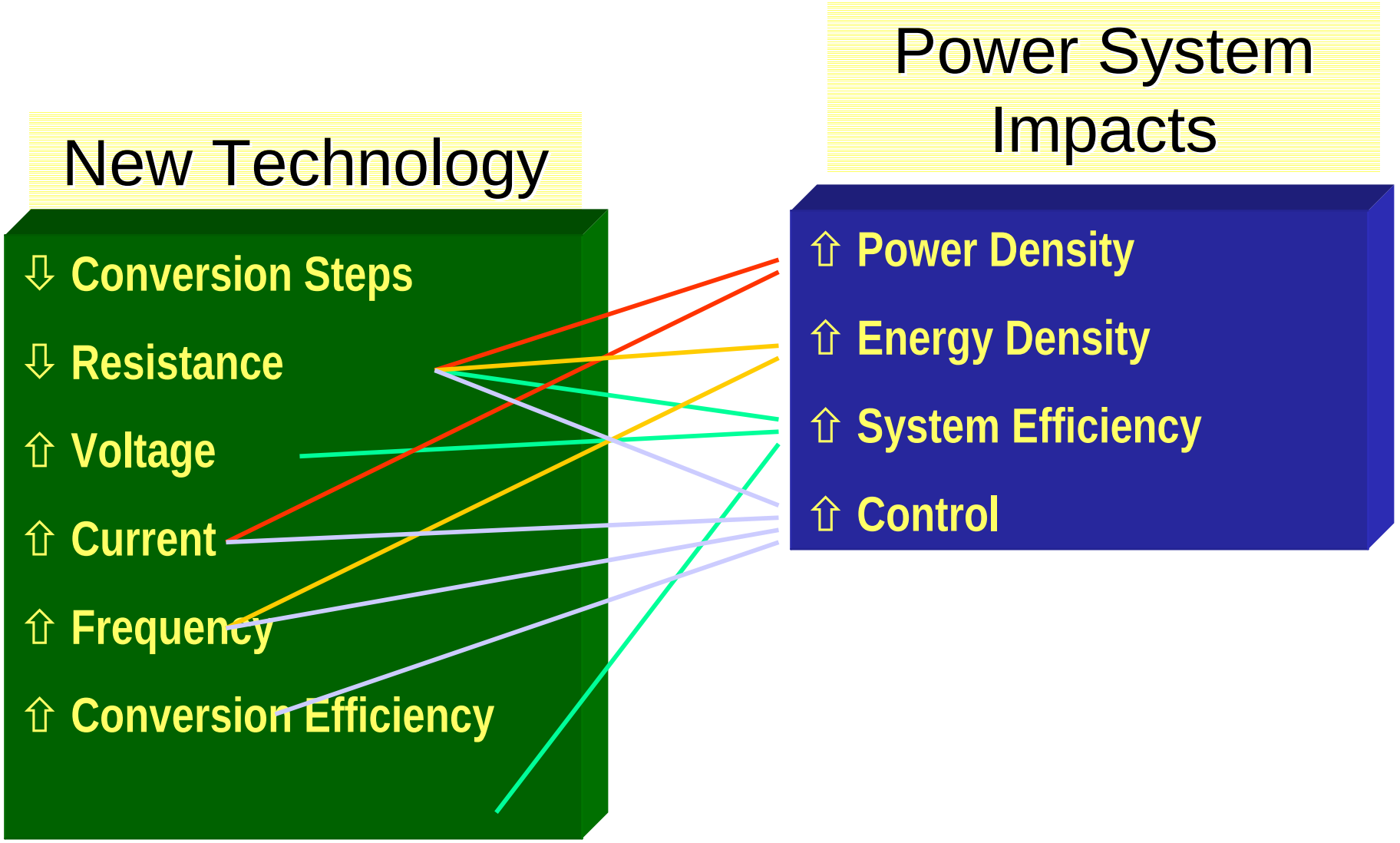
221 ft.

An Electric Navy Ship = 10x Cruise Ship Power Density

With pulse power, An Electric Warship = 20x Cruise Ship Power Density

Metrics	Fantasy Cruise Liner	Navy Littoral Combatant
Length, max: ft. Breadth, DWL: ft . Draught, DWL: ft.	856 103 26	221 22 7.2
Displacement: LT	~40,000	~2,000
Total Propulsion & Service Power Output: kW	42,240	~15,000→ 20,000
Specific Power Output: kW/LT	1.1	~7.5→10

Technology Impacts on Power Systems

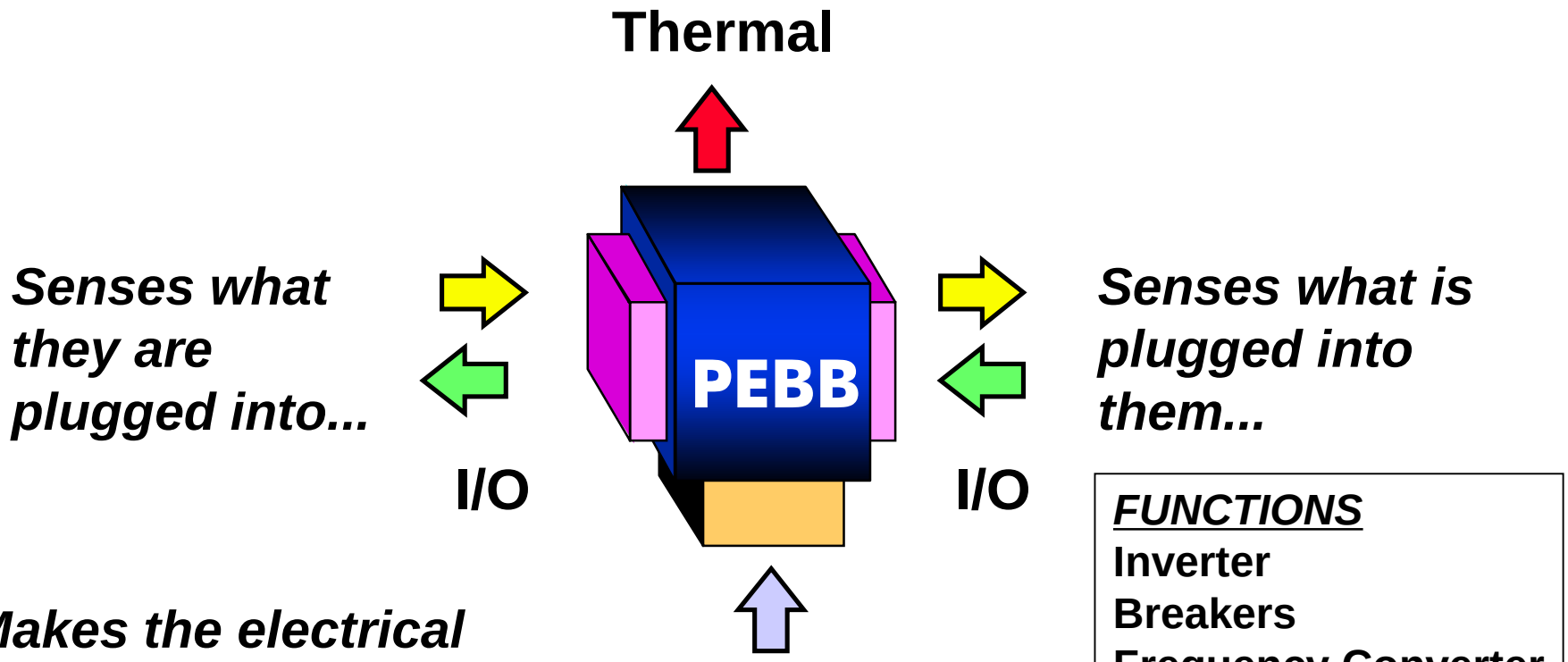


Integration

- Modularity generally increases size, weight, & cost
  - But, Integrated Modularity can lead to far lower cost, size, & weight
- Integrated Modularity Attributes for power systems
  - Partitioning based on Physics
    - Thermal, Mechanical, Electrical, & Control
  - Cellular design
    - Material-to-system design rules
    - Hierarchical design objectives
  - Programmable performance
    - Variable output range
    - Multifunctional hardware modules
    - System reconfiguration

Surface & Subsurface Platforms

PEBB Systems: A Simple Set of Blocks for Power Electronics

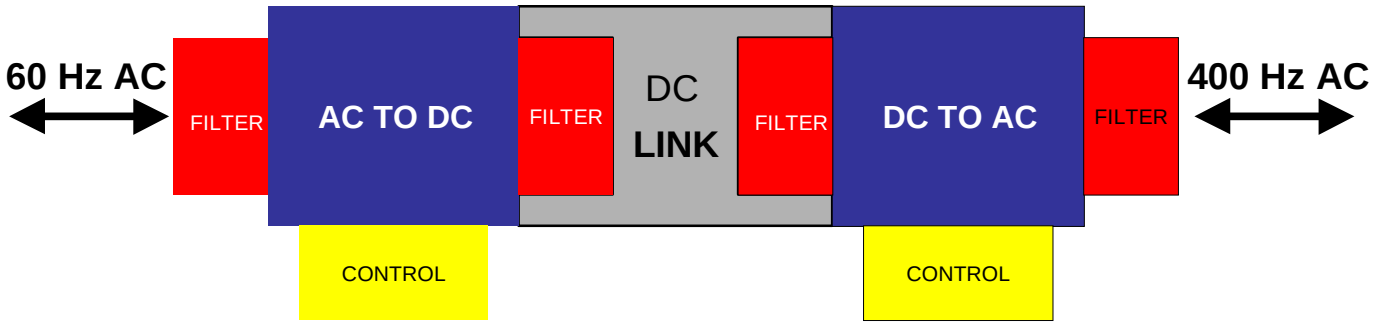


Like a child's set of blocks

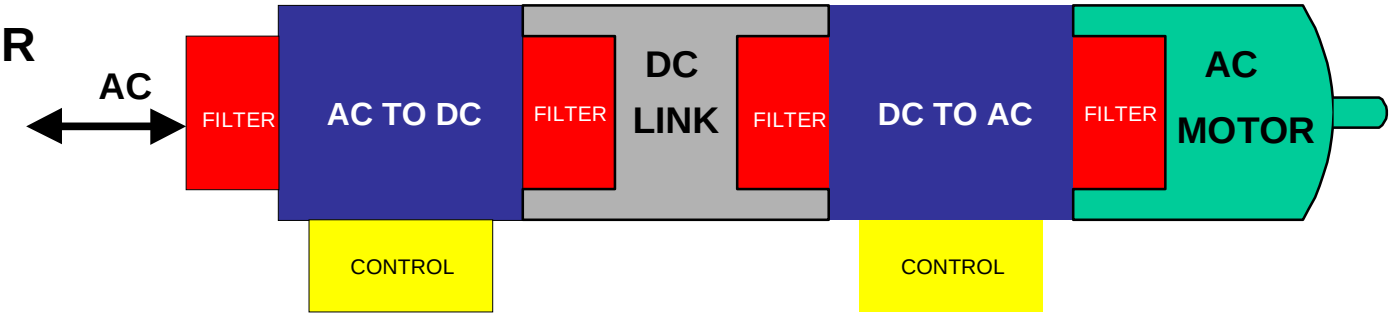
A Simple Set Of Blocks For All Power Needs

Surface & Subsurface Platforms

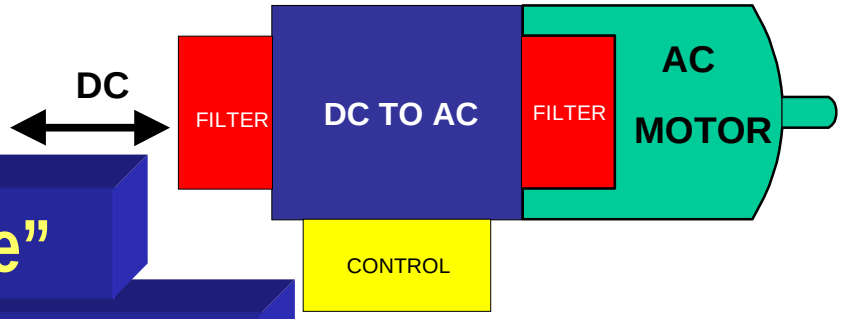
FREQUENCY CONVERSION USING TWO PEBB INVERTERS



AC TO AC MOTOR CONTROLLER USING TWO PEBBS



MOTOR CONTROLLER FROM A DC SOURCE



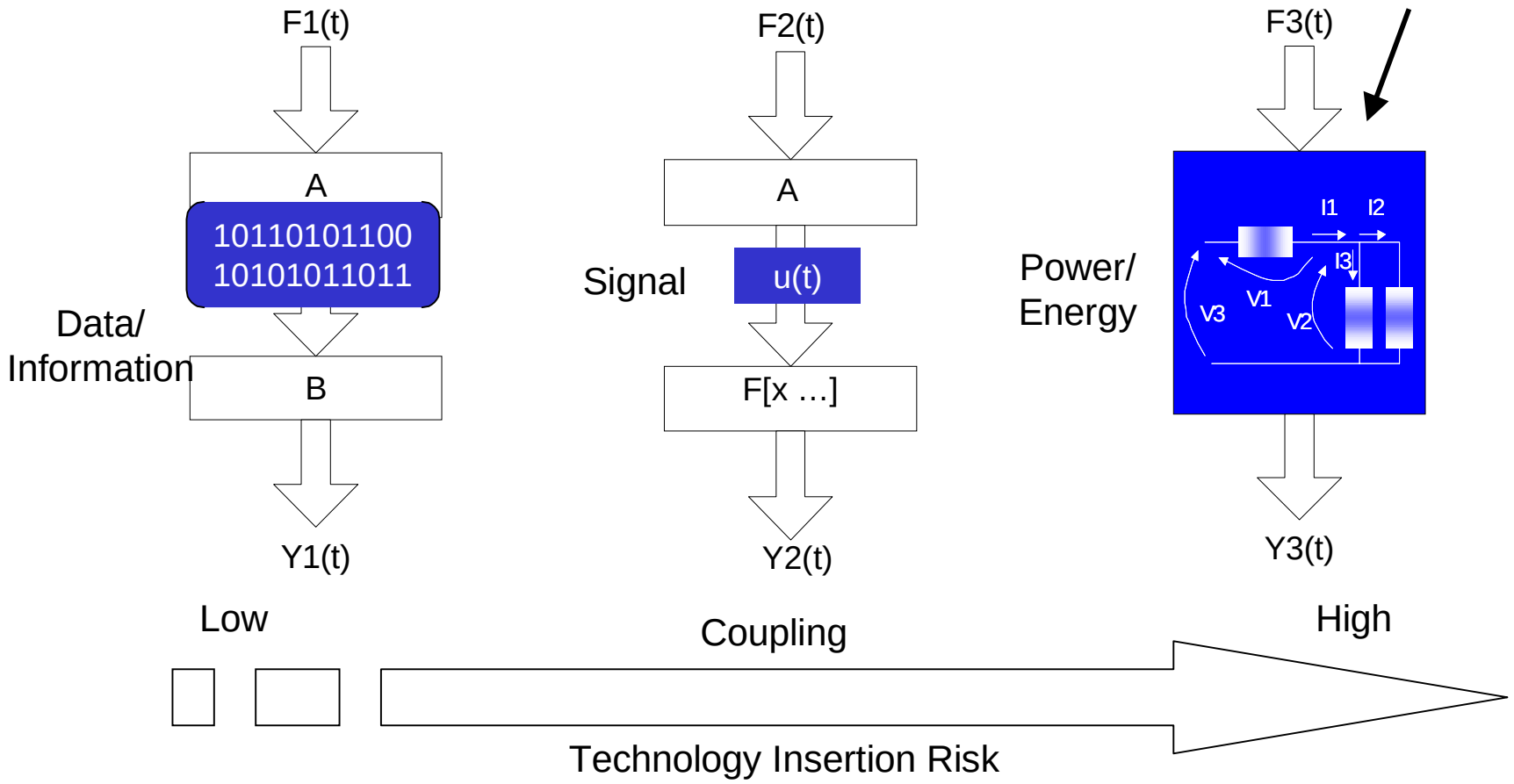
"Open Plug and Play Architecture"

"Like a child's set of blocks"

Surface & Subsurface Platforms

System Coupling

Must obey conservation laws



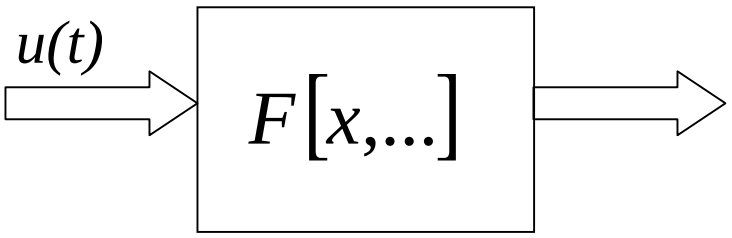
Three types of interactions between objects as defined by the IEEE, VHDL-AMS (VLSI Hardware Description Language - Analog and Mixed Signal)

Surface & Subsurface Platforms

Physics Based Partitioning

Control

Signal, unidirectional $y(t)$
(Temporal partitions)

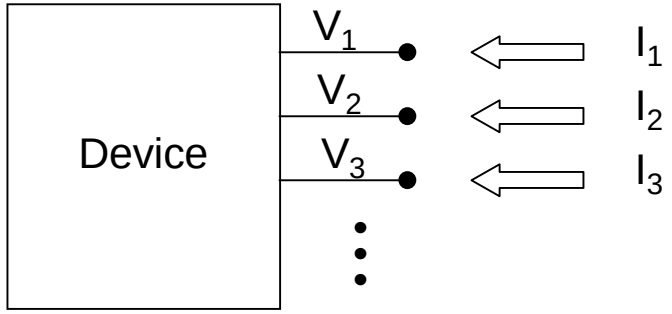


$$\dot{x}(t) = f[x(t),u(t),t]$$
$$y(t) = g[x(t),u(t),t]$$

$x(t)$: State vector
$y(t)$: Output vector
$u(t)$: Input vector

Stability

Natural, bi-directional
(Spatial, i.e. electrical, mechanical, and thermal partitions)



$$\begin{bmatrix} i \\ 0 \end{bmatrix} = \begin{bmatrix} f_1(\dot{v},\dot{y},v,y,u) \\ f_2(\dot{v},\dot{y},v,y,u) \end{bmatrix}$$

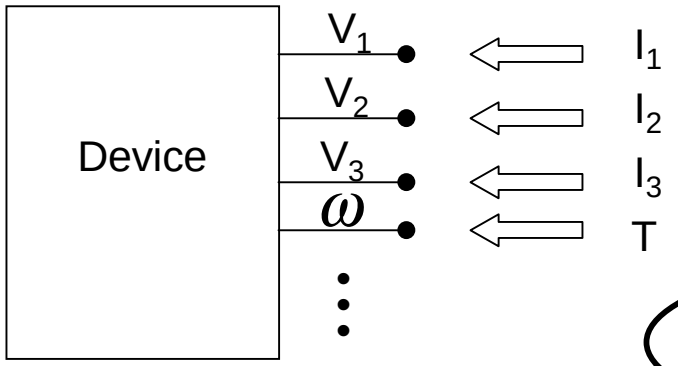
v: Vector of terminal through variables (voltages)
i : Vector of terminal across variables (currents)
y: Vector of device internal state variables
u : Vector of independent controls

Signal & Natural combined to form Functional partition definitions

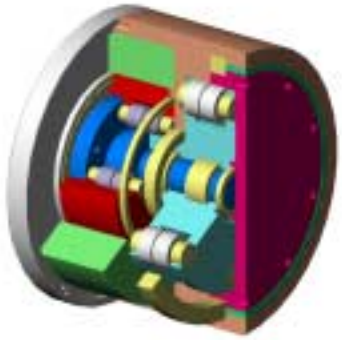
Partitioning Variables -- electrical, thermal, and mechanical

Type	*Across Variable*	*Through Variable*
Electrcial	Voltage (Volts)	Current (Amperes)
Mechanical (Linear)	Speed (m/sec)	Force (Nt)
Mechanical (Angular)	Angular Speed (rad/sec)	Torque (Nt-m)
Hydraulic	Pressure (Nt/m^2)	Volume Velocity (m^2/sec)

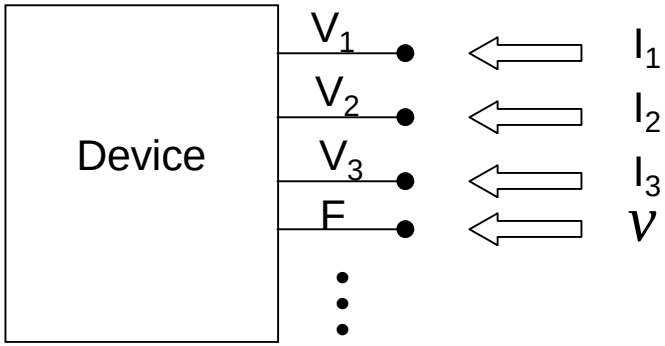
Building Blocks & Actuator Challenges



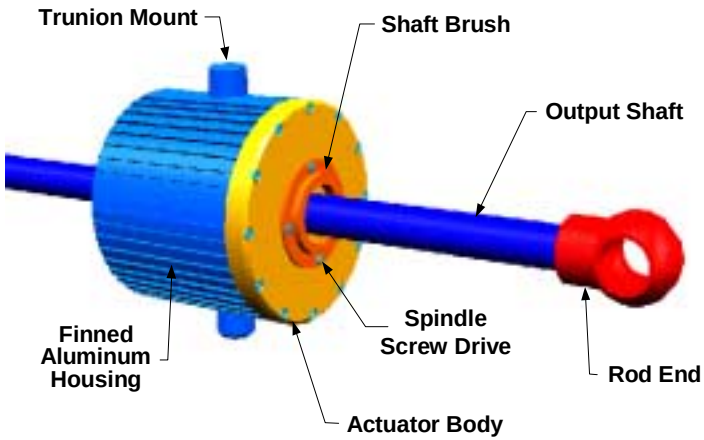
Epicyclic Cylindrical Actuator



Mechanical and strength of materials at issue



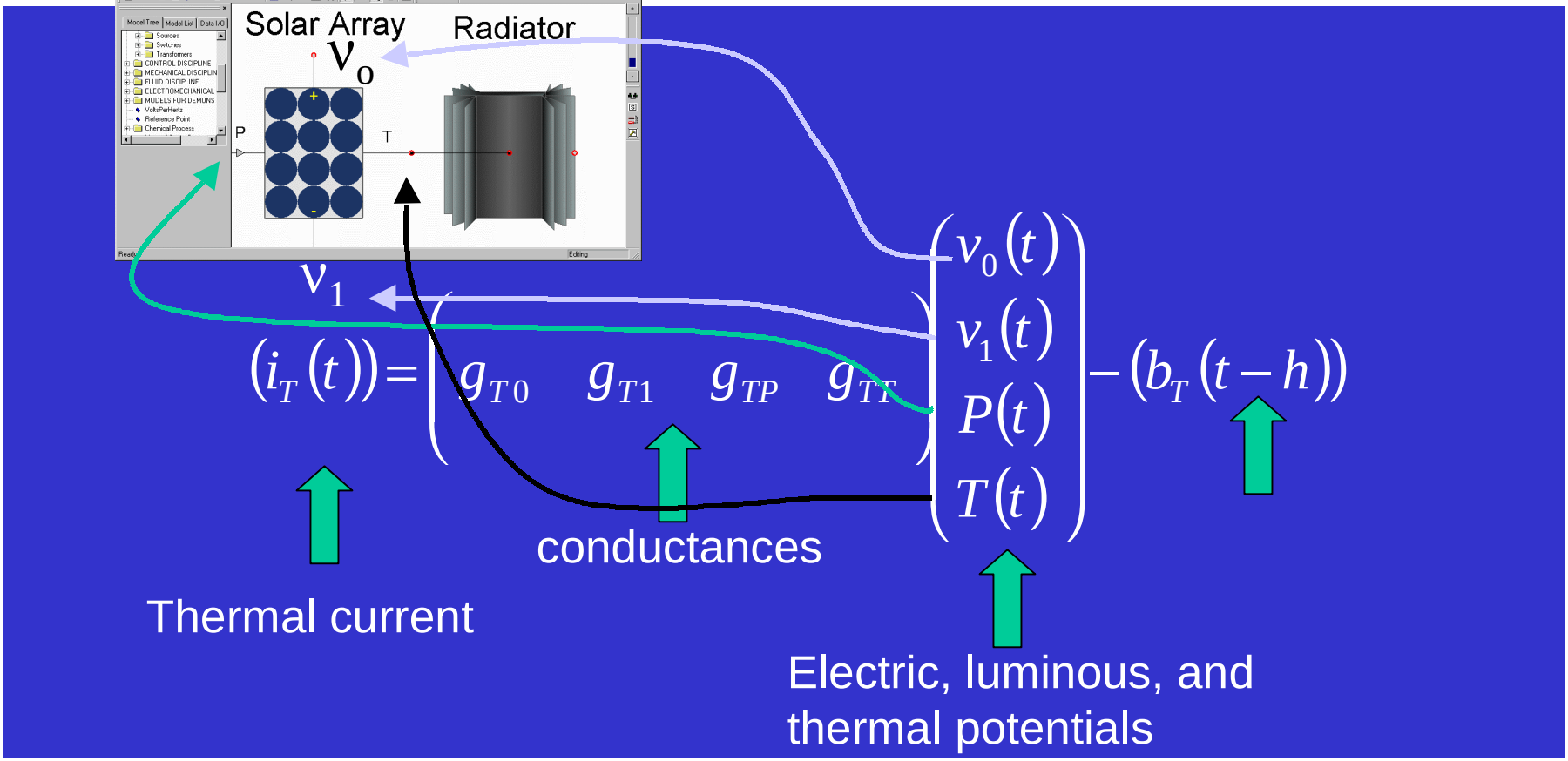
Frameless Linear Actuator



Motor issue -- force, speed, and control

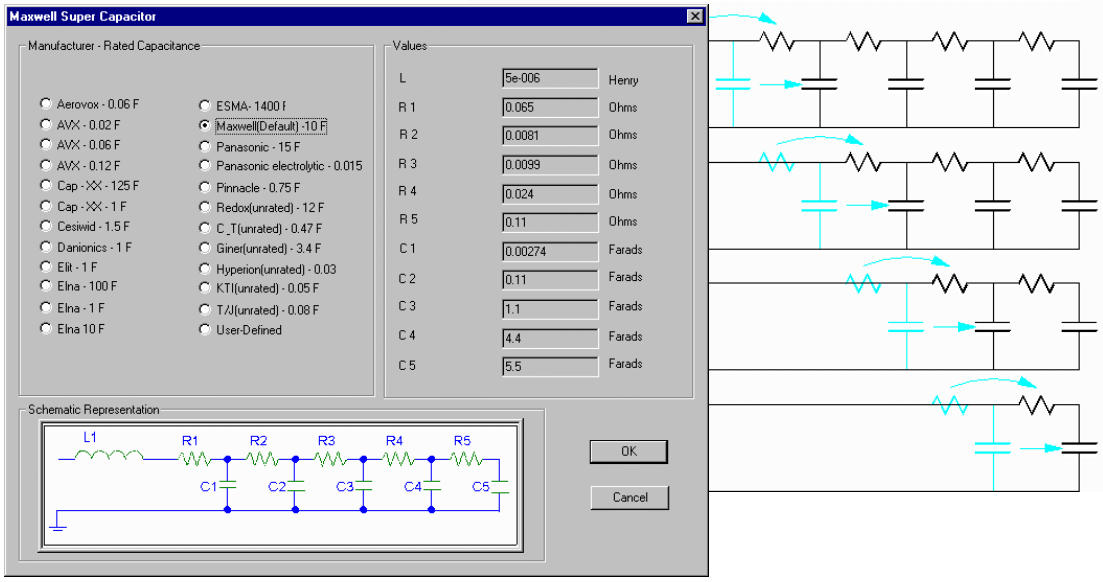
Surface & Subsurface Platforms

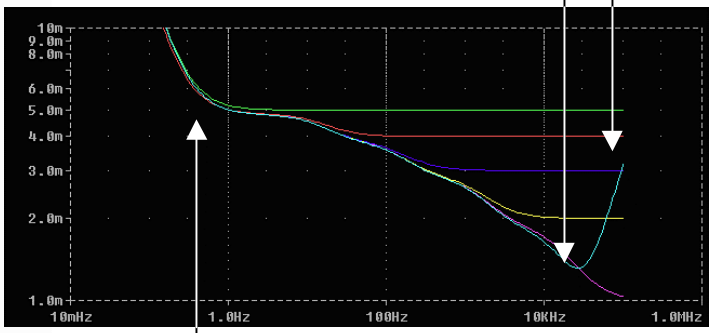
Natural Coupling Example: Thermal Terminal for Solar Array



Analysis Using the Virtual Test Bed -- VTB

Hierarchical Issues: Variable model order Example: supercapacitor

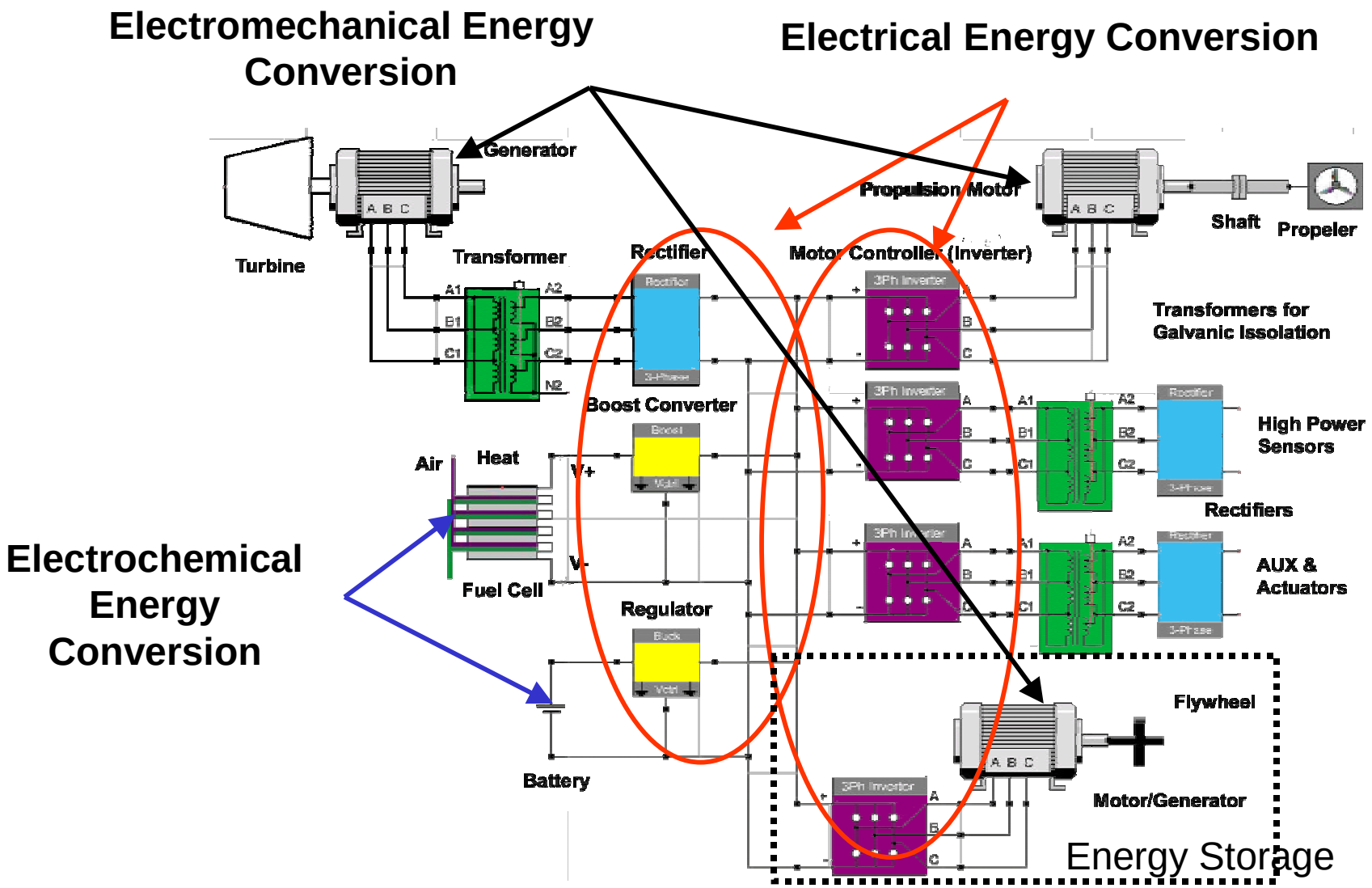




Frequency response

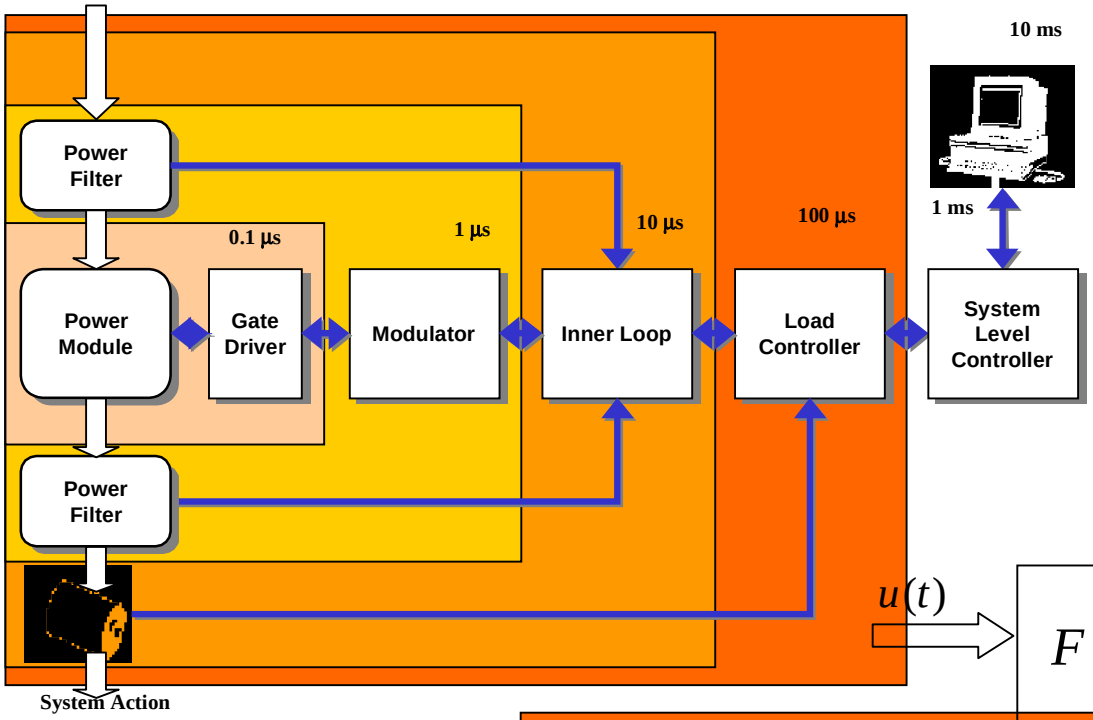
Electrical Power Systems Technology (Physics Based -- Natural Coupling)

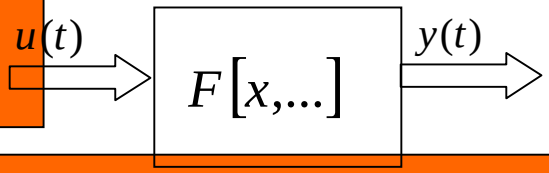
Surface & Subsurface Platforms

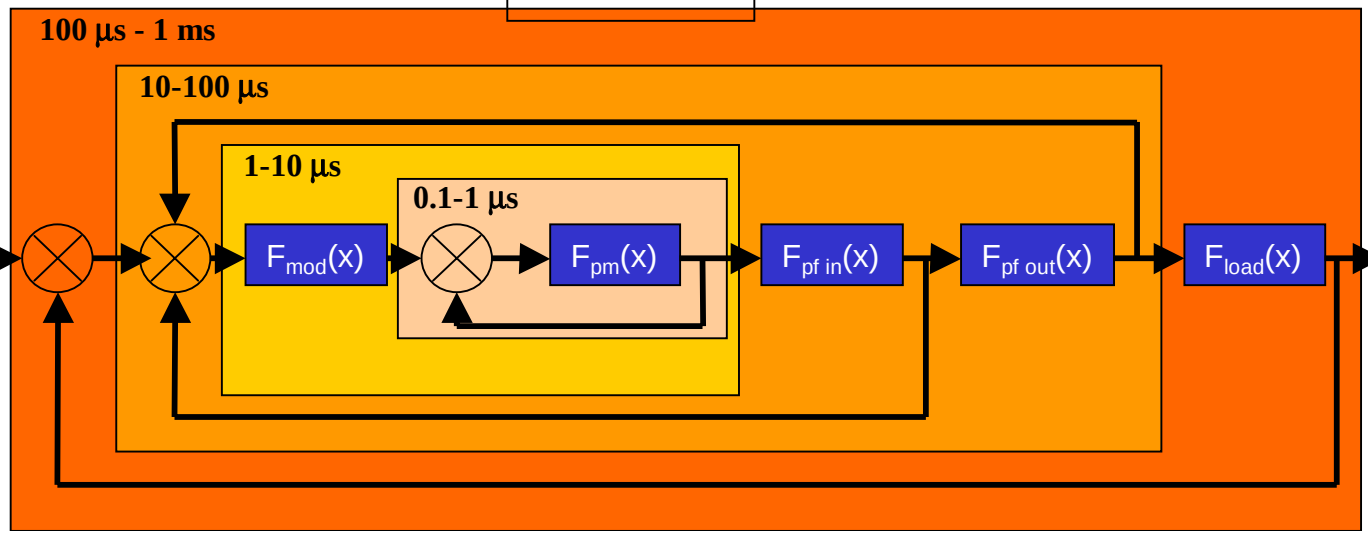


Surface & Subsurface Platforms

Physics Based Temporal Partitions, Control

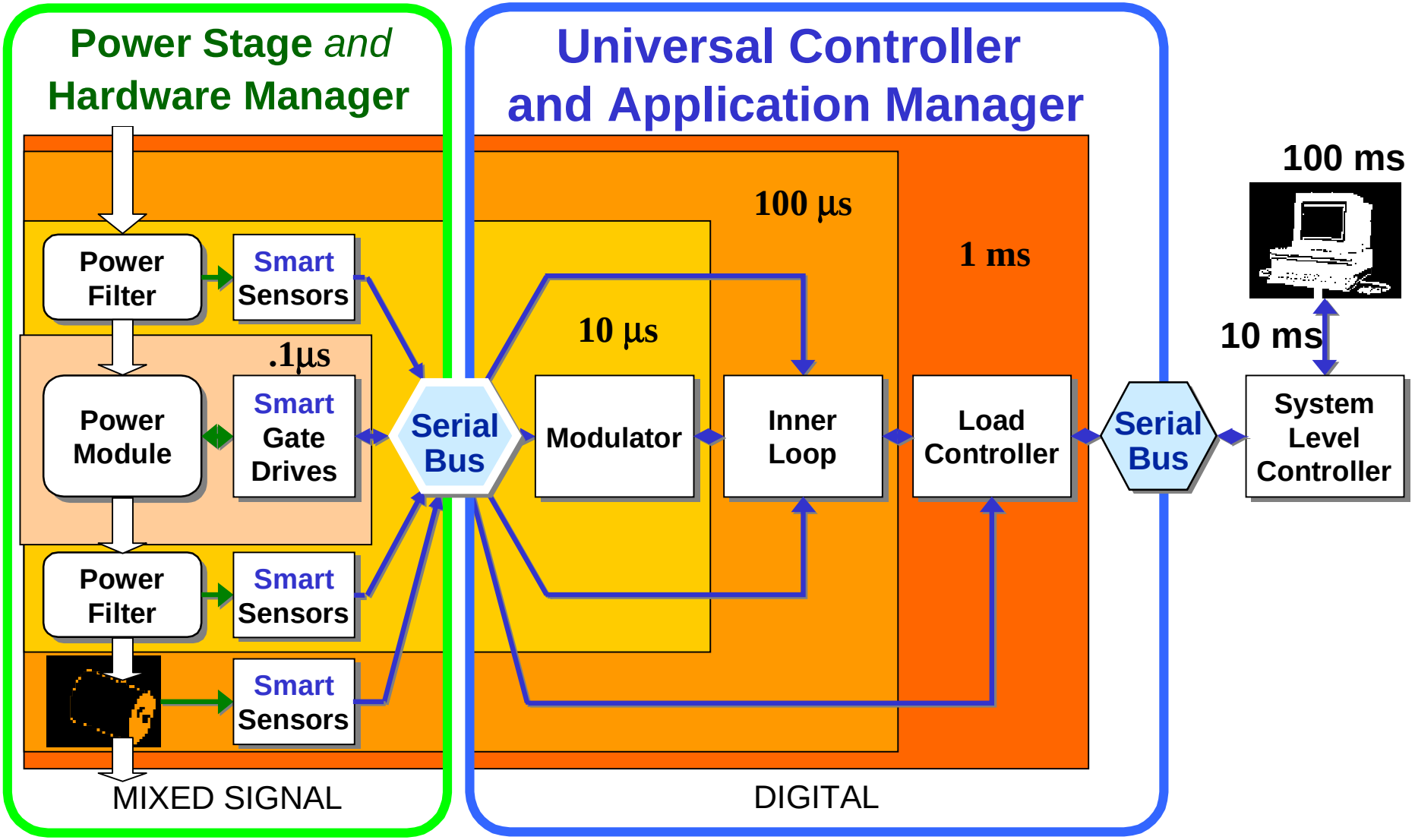






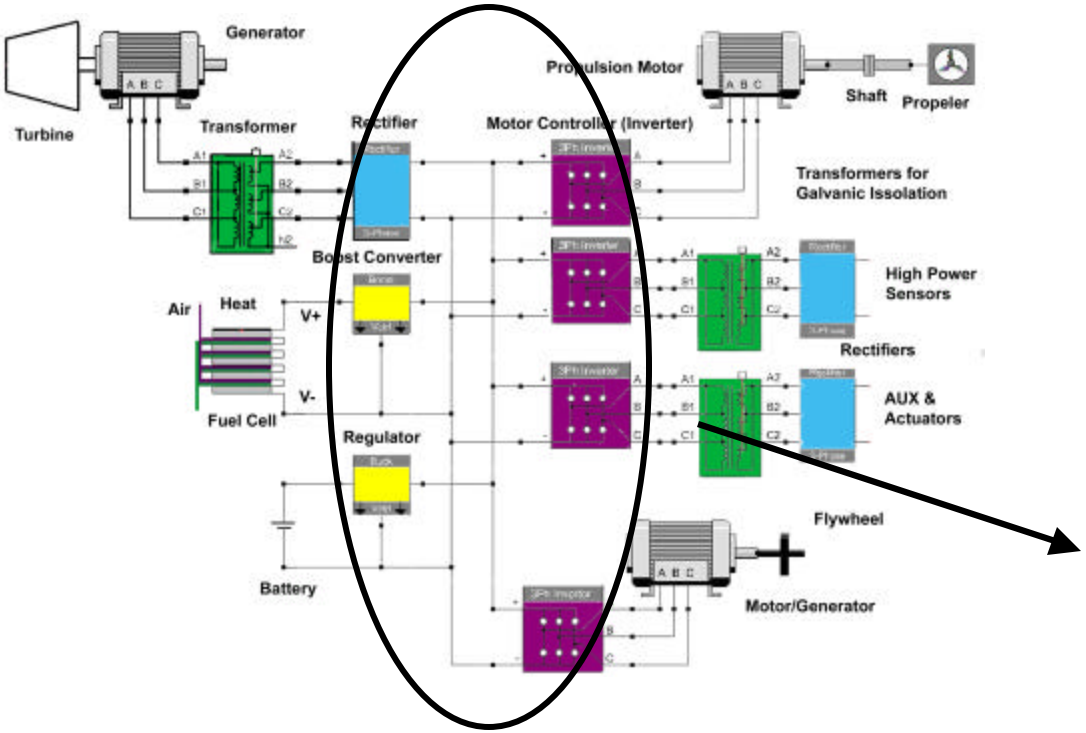
Universal Controller Architecture under Development with serial, fiber optic, bus interfaces

Surface & Subsurface Platforms

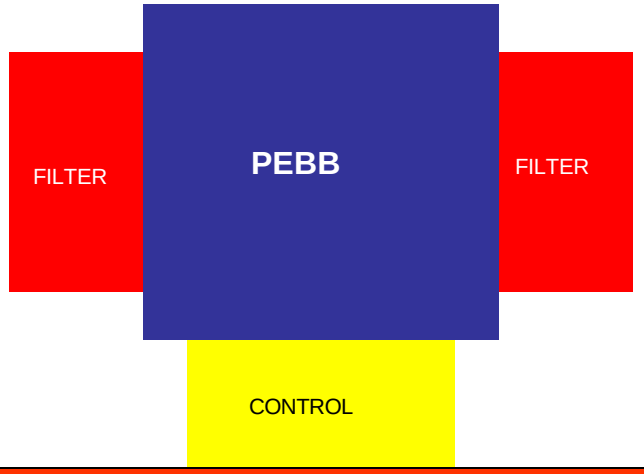


Standardization

Surface & Subsurface Platforms



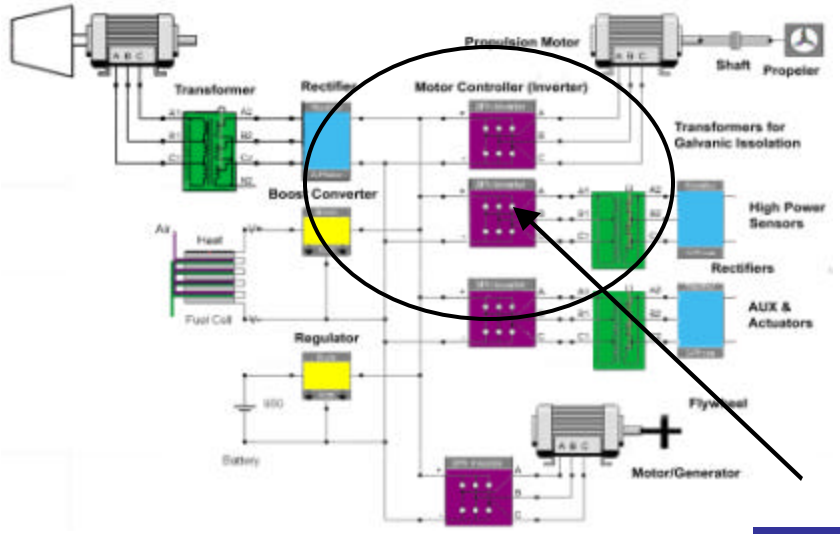
- ⇩ Conversion Steps
- ⇩ Resistance
- ⇧ Conversion Efficiency
- ⇧ Voltage
- ⇧ Current
- ⇧ Frequency



Power Electronic Building Blocks (PEBB):

- Pre-engineered, pre-tested, plug & Play building blocks for high power controllers.
- Software programmable for multifunctionality.
- Industry based – adoption initiated, IEEE WG I-8, Power Electronic Building Block Concepts – 2 IEEE tasks: PEBB Technology & Digital Control Architectures (Universal Controller)

Focus on Critical Components for High Power Converters



PEBB

3-5x reduced loss

- double-side power device
- wide bandgap SiC device
- SiC rectifier

30 KV, low loss

FILTER

AC

FILTER

10x smaller size

capacitor & inductors

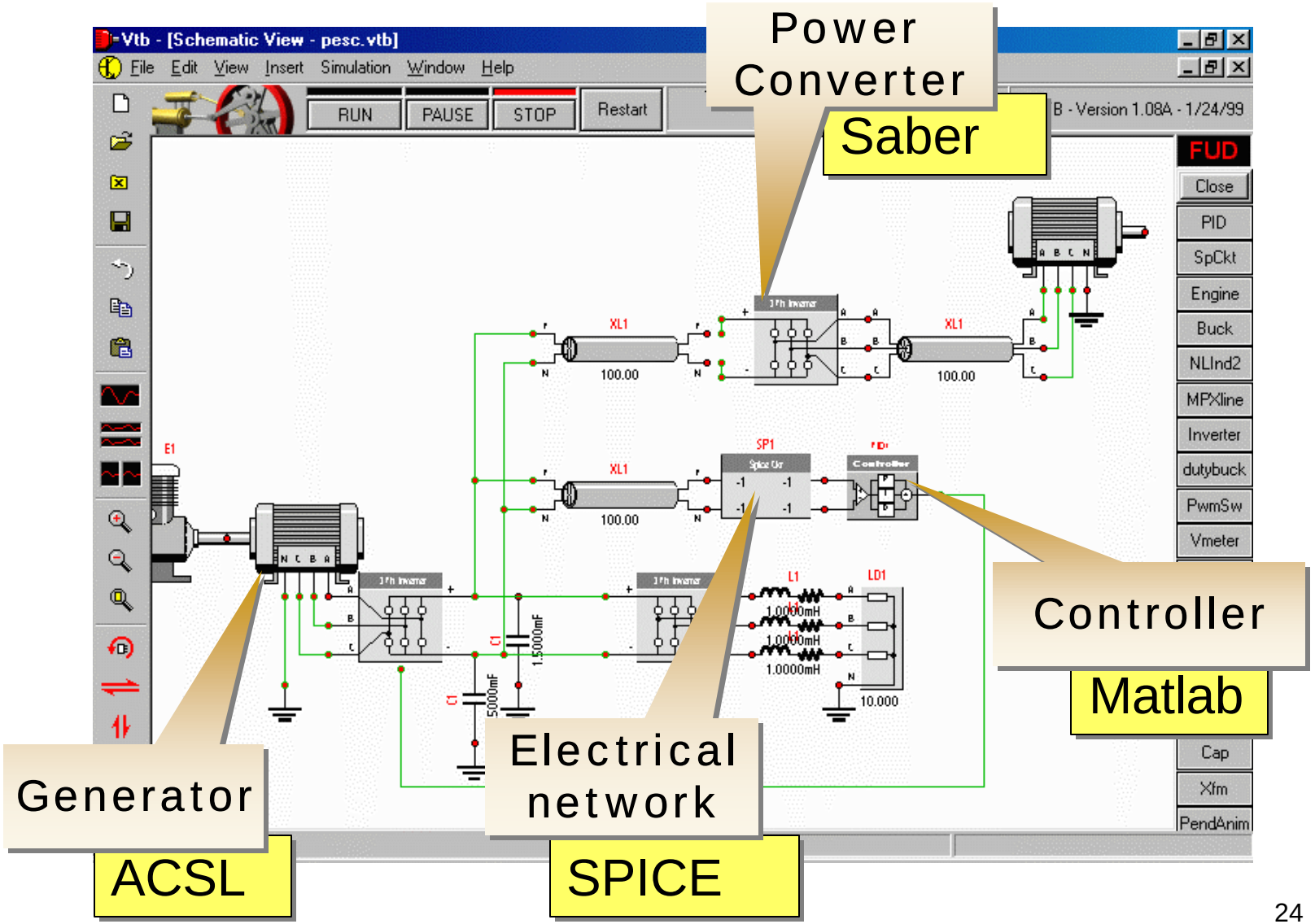
capacitor & inductors

THERMAL CONTROL

diamond & AlN substrate

Surface & Subsurface Platforms

The VTB is an environment for collaborative design and virtual prototyping of advanced power systems



VTB -- Modeling and Simulation Interactions

SPCO

Sim-Stim

Cambridge (England)

Northrop Grumman

Newport News Shipbuilding

Virginia Tech

USC

Politecnico di Milano (Italy)

Interactive Data Visualization

Power Paragon

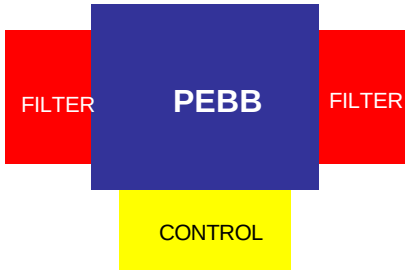
Georgia Tech

CAPS/FSU

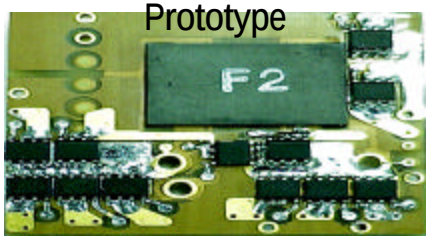
Taganrog St Univ (Russia)

Surface & Subsurface Platforms

Products

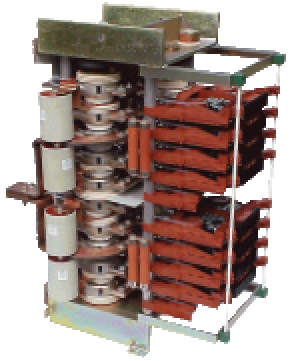


1.5V / 100W Rockwell Prototype

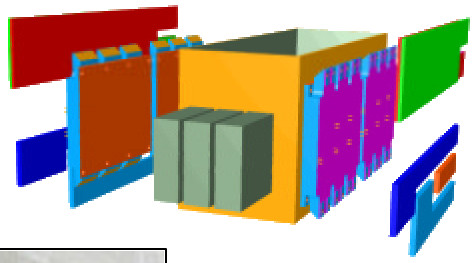


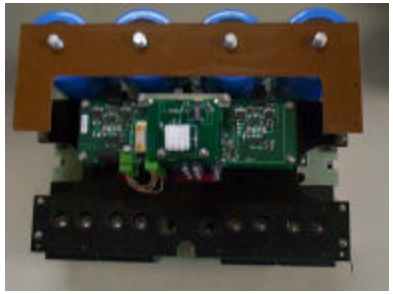
1.81” x 1.73” x 0.32”

ABB 9MVA PEBB



Rockwell R-PEBB





Silicon Power PEBB

DoE, Automotive Inverter Power Module, AIPM, by Silicon Power

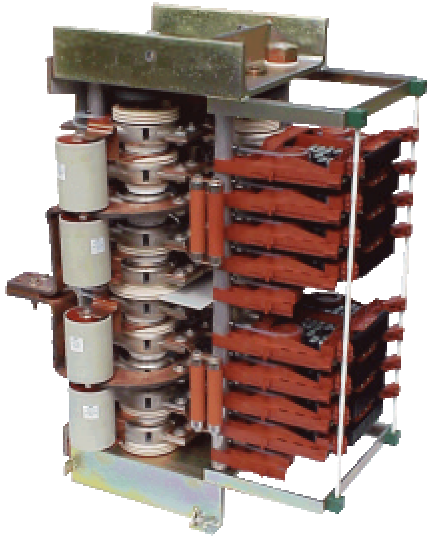
Only as big as your Shoe!

Tested at 30kW steady state, 55kW pk and 300A peak operation

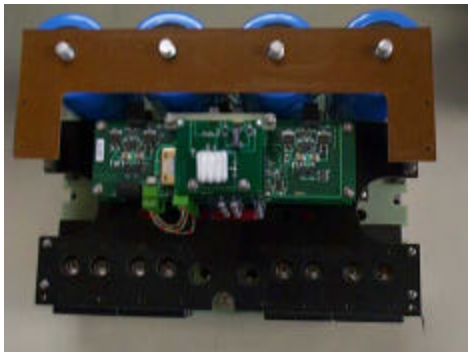
Major Performers: ABB, Rockwell, Silicon Power, Northrop-Grumman, NSWC, GDDS, Va Tech, NRL, DoE

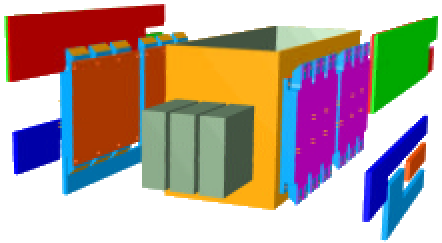
Surface & Subsurface Platforms

PEBB Types Transitioned to Engineering

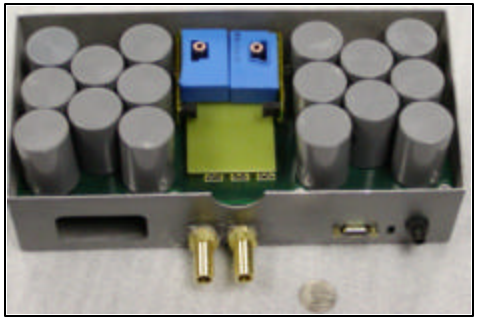


3-Terminal PEBB





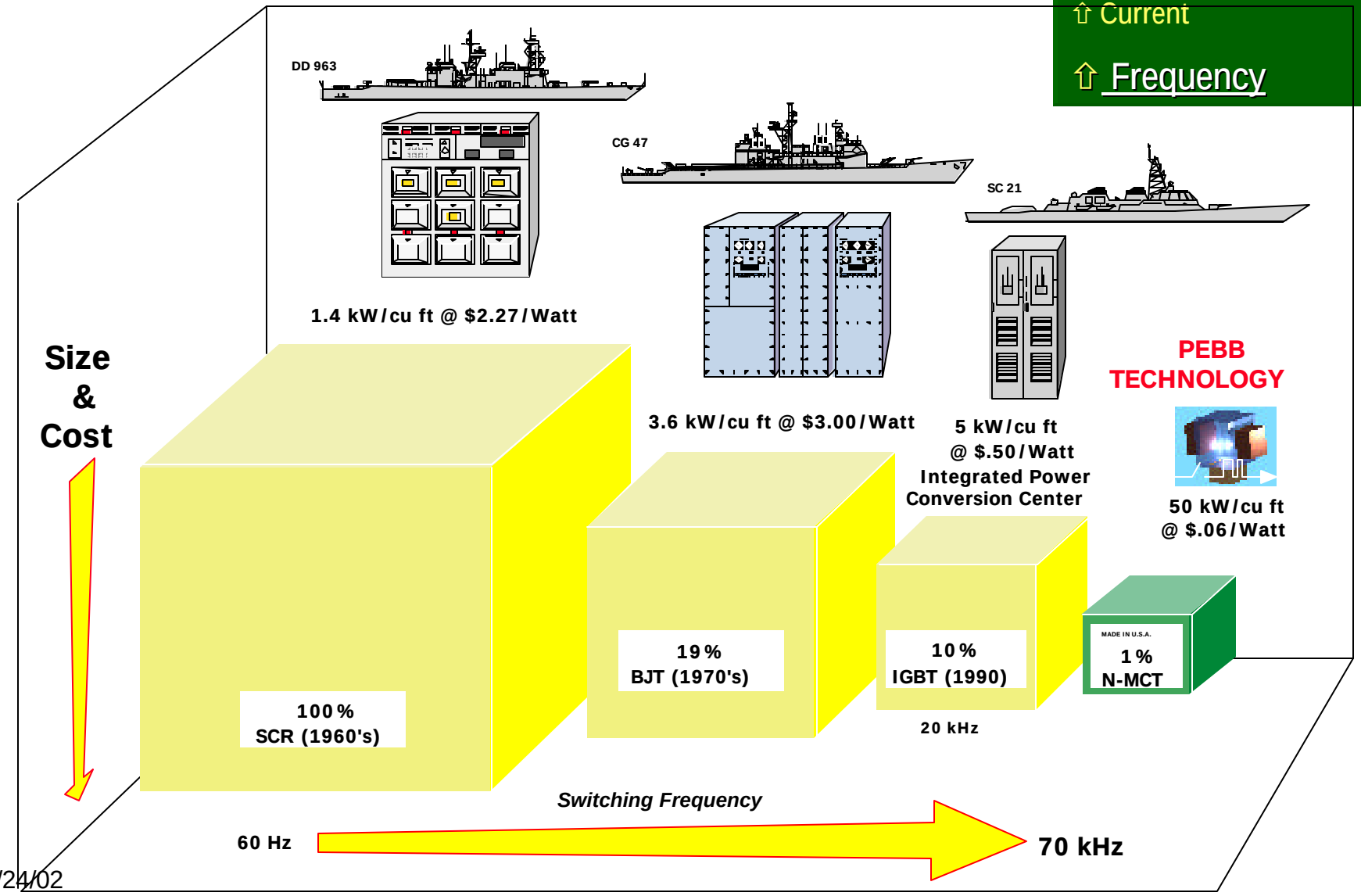
5-Terminal PEBB



Surface & Subsurface Platforms

Shipboard Power Supplies & Controllers

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



Surface & Subsurface Platforms

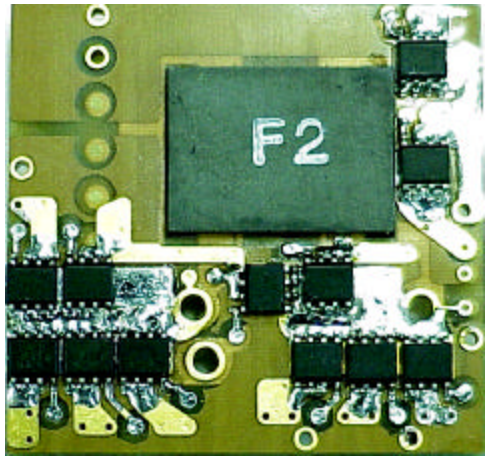
High Density & High Efficiency GaAs Point of Use Power Supply

Purpose

Develop 3.3V & 1.5V 100W output dc-dc power converters

- efficiency 90-95%
- power density > 100 W/in^3
- reliability > 50,000 h MTTF
- cost < $50
- status: complete

1.5V / 100W
Rockwell Prototype



1.81” x 1.73” x 0.32”

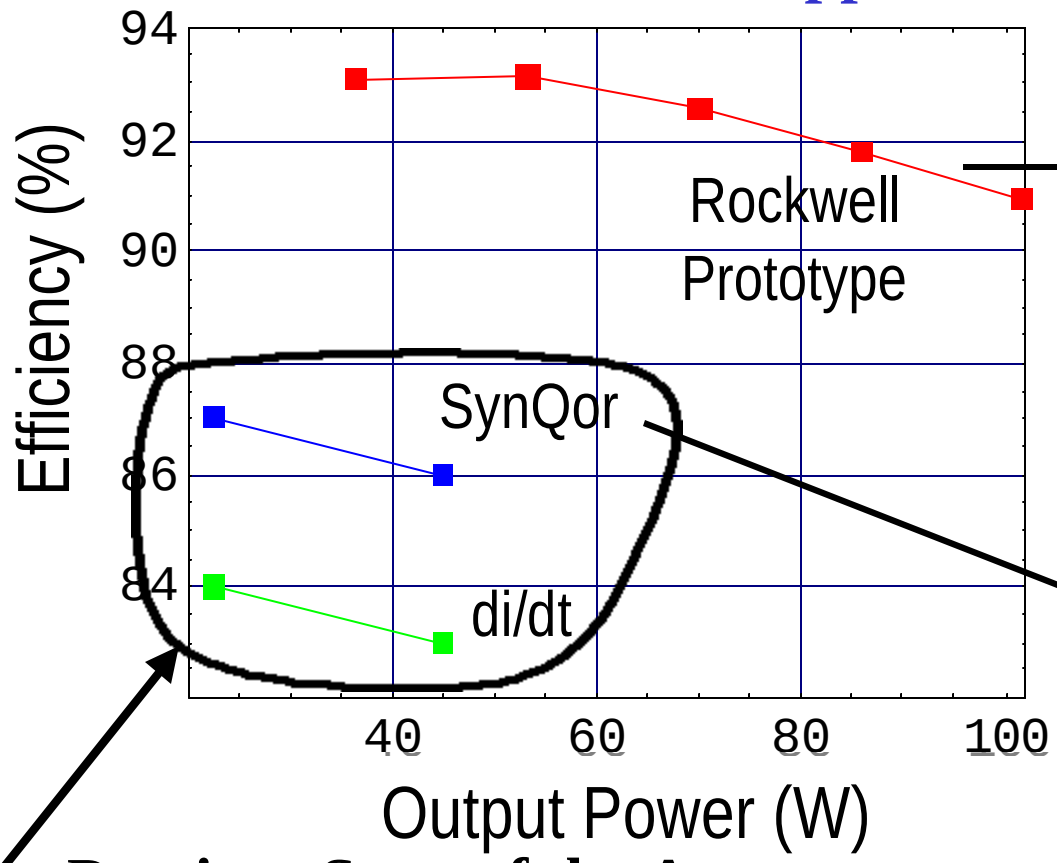
Rockwell Collins

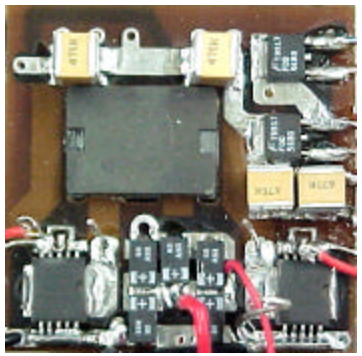
Rockwell Scientific

Surface & Subsurface Platforms

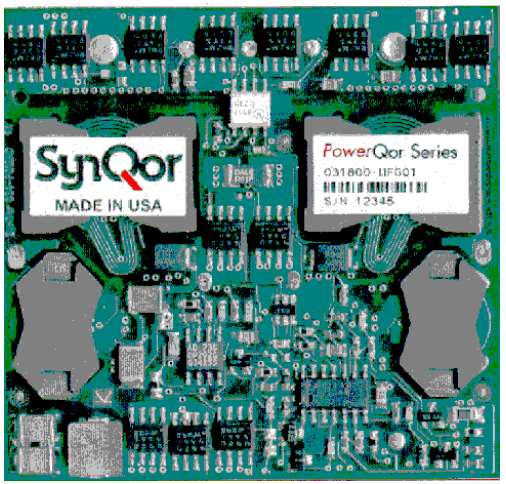
Accomplishment Summary

Point of Use Power Supplies





88-100 W/in ^{3}



20-45 W/in ^{3}

Previous State of the Art

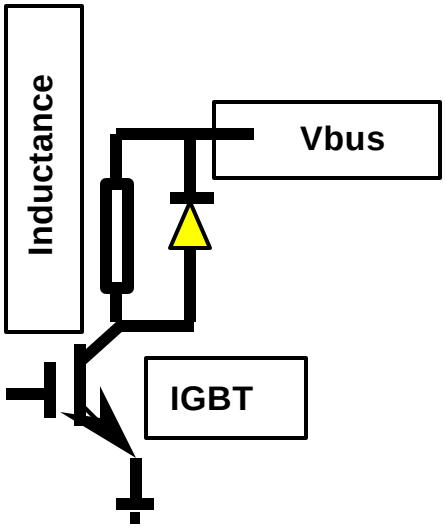
Generally not applicable to large (Megawatt) Power Supplies.

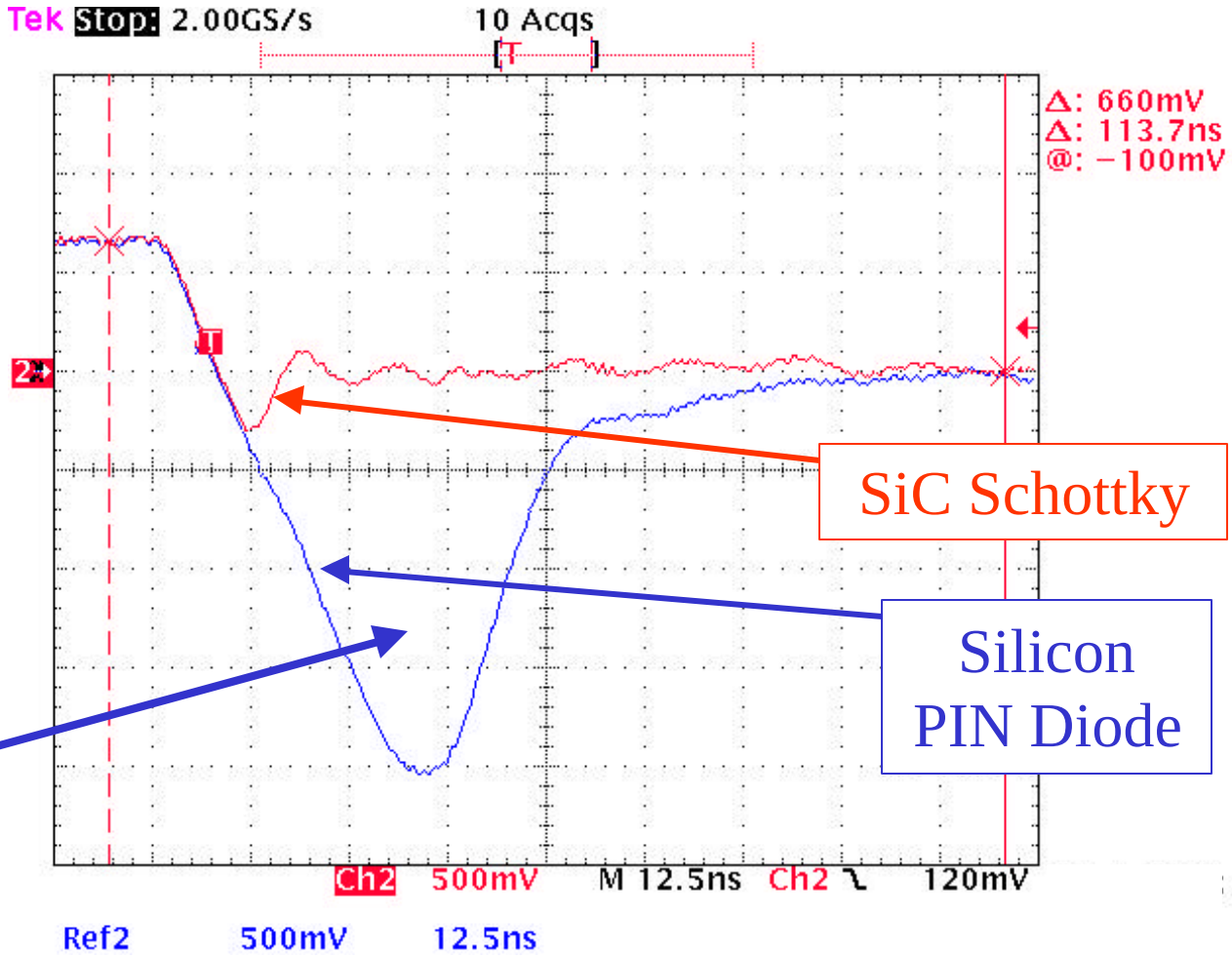
Rockwell Collins

Rockwell Scientific

Surface & Subsurface Platforms

Advantages of SiC in Hybrid Circuit Composed of a Si Switch and SiC Commutator Diode





Reverse swing area represents loss

SiC Schottky

Silicon PIN Diode

- 4x lower recovery time
- 7x lower reverse peak current

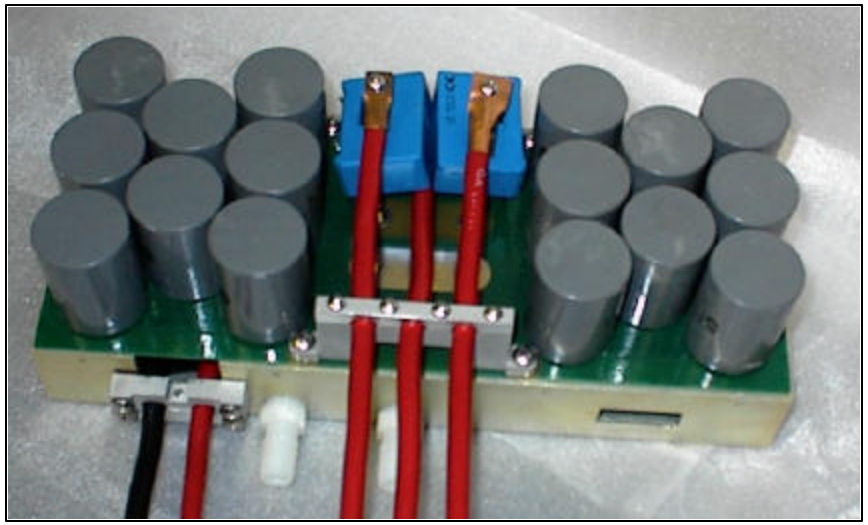
$\Rightarrow$ reduced switching loss

600 V fly back diode

24 -fold FOM Improvement

Surface & Subsurface Platforms

Mid-Program ThinPak-based AIPM Pre-Alpha Unit



Overall Characteristics

Length: 11.375” x Depth: 4.75” x height: 4.0”

Volume: 216.125 inch^3 (3.43 liters)

Weight: 7.25 Lbs (3.3 Kg)

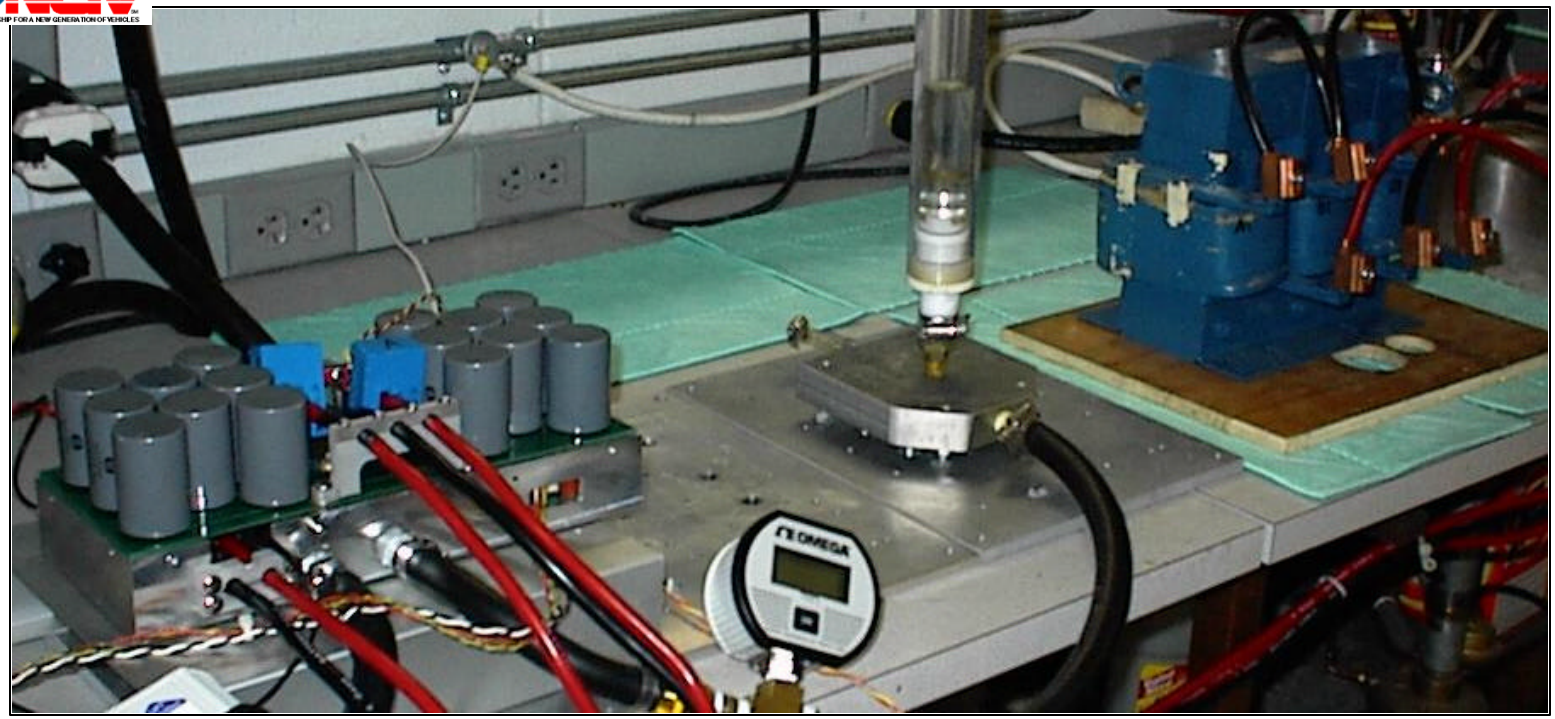
Only as big as your Shoe!

Tested at 30kW steady state, 55kW pk and 300A peak operation

SILICON POWER

Surface & Subsurface Platforms

Pre-Alpha Unit Meets 55 kW Power Level at 70C Coolant with Test Load



Pre-Alpha Unit 1 test conditions
(applies to all the data presented in the following slides)

Coolant type : Distilled Water
Coolant temp : 25ºC
Coolant Flow rate : 1.5 gpm

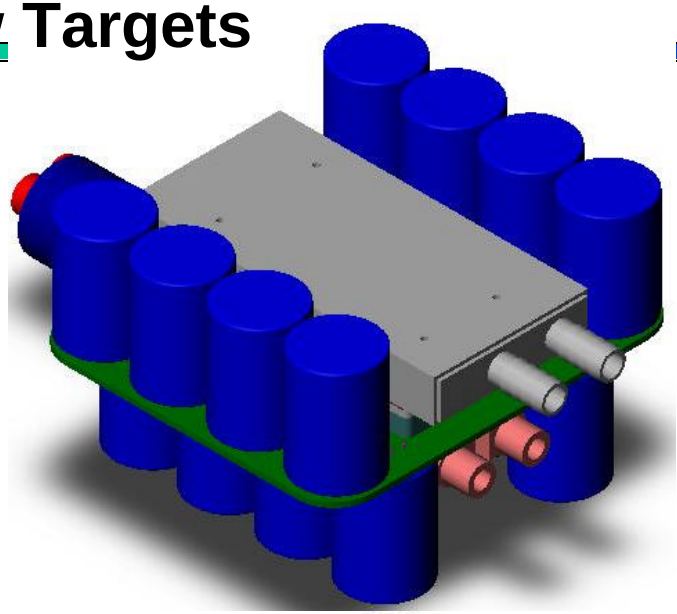
DC Bus = 260 V
Switching frequency = 12 kHz
Output frequency = 200 Hz

100 uH 3-phase Inductive load at 55kW (300A peak phase current)

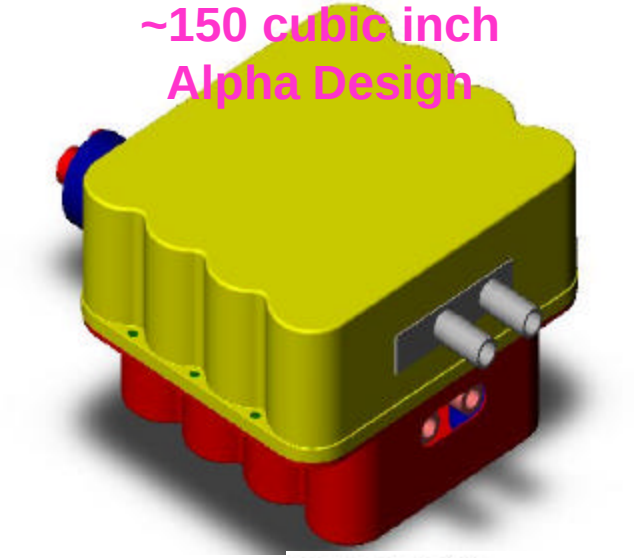
SILICON POWER

Surface & Subsurface Platforms

Final Year Brings Volume, Weight and Cost Well Below Targets



~150 cubic inch
Alpha Design



Volume reduction to ~ 150 cubic inches

Cost reduction (100K units/year at < $7/kW

Weight to < 10 pounds

SILICON POWER

Surface & Subsurface Platforms

Rockwell PowerFlex Product Family

PowerFlex
Powerful Performance. Flexible Control.

PowerFlex 7000
Powerful Performance. Flexible Control.

PowerFlex 700

PowerFlex 70

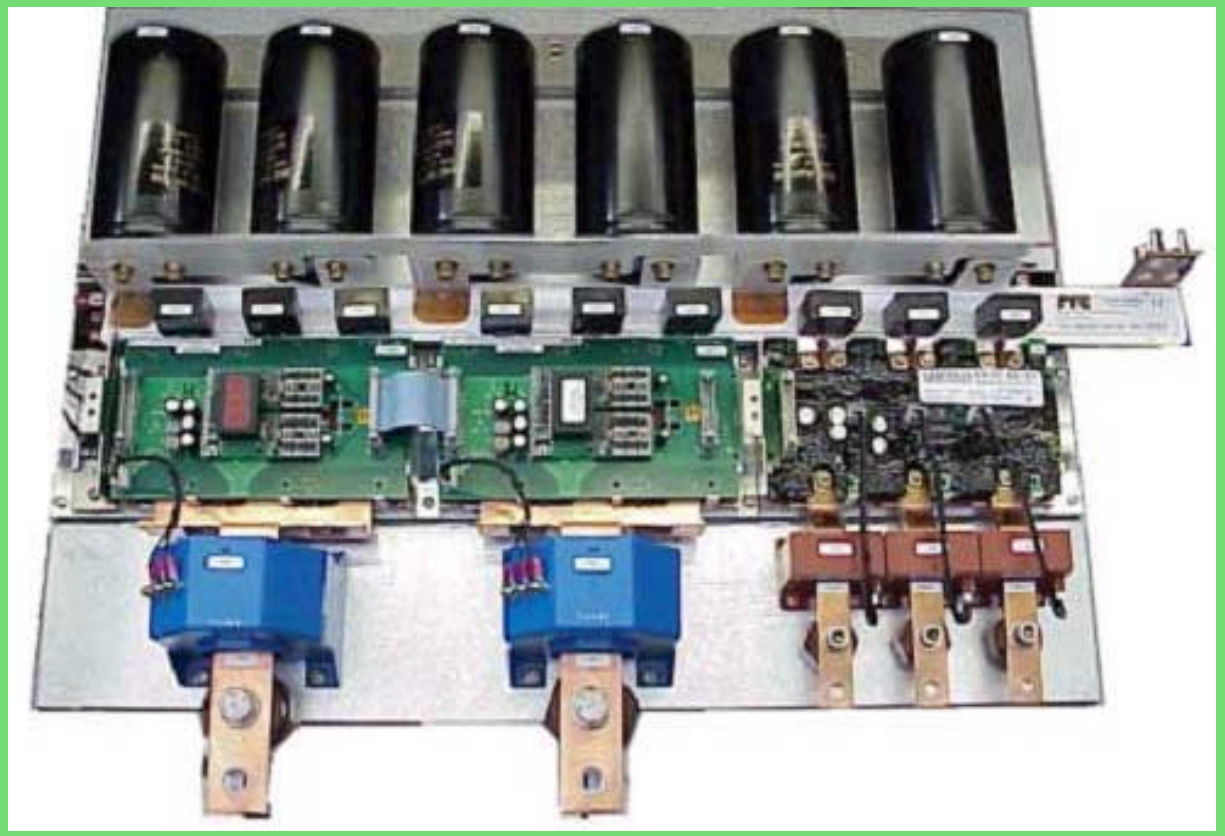
R-PEBB

Allen-Bradley
Rockwell Automation
Rockwell Science Center

New R-PEBB Product 1Q 2001, built on PEBB design, 2x improved

ABB IGBT PEBB

- A new low-voltage PEBB developed with the US Office of Naval Research



PowerPak3

Surface & Platforms

ABB IGBT PEBB - Scalability

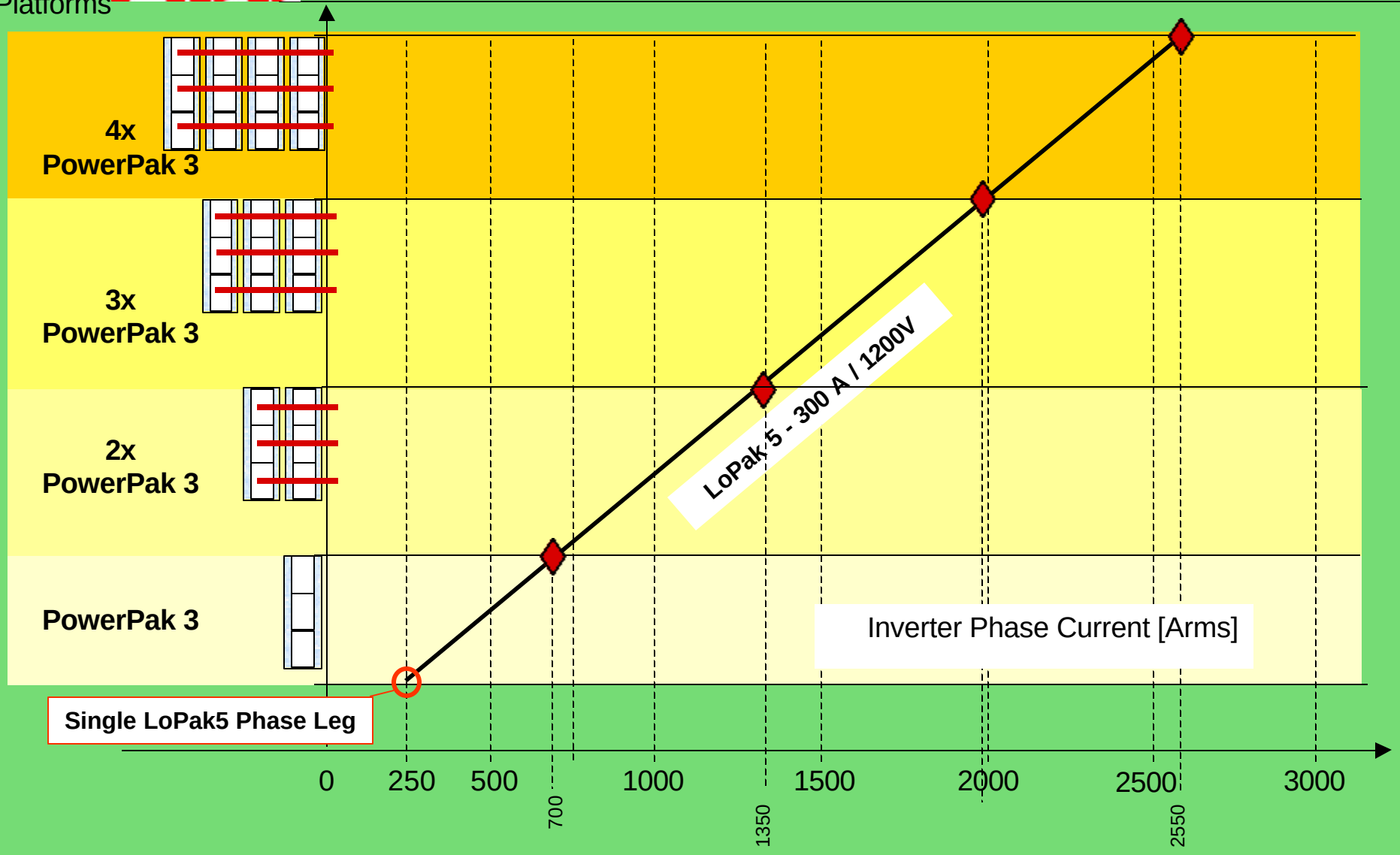
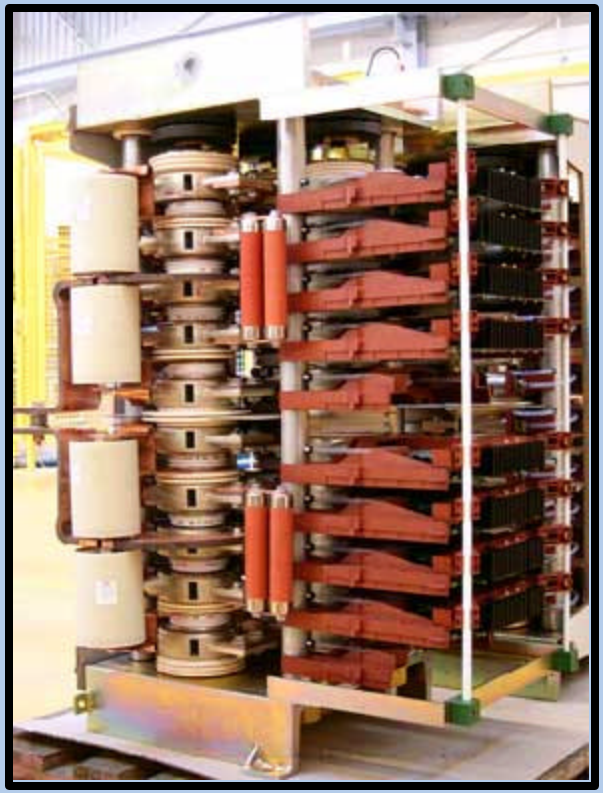


ABB IGBT PEBB - Flexibility

- Uses 3 IGBT modules with 3 phase-legs each
- Positive temperature coefficient permits easier paralleling
- PowerPak3 can provide various configurations, e.g.
  - 1 x 3-phase converter (3 phases)
  - 1 x 1-phase H-bridge + 1 x 3-phase converter (5 phase legs)
  - 3 x 3-phase converters (9 phases)

ABB IGCT PEBB

- Power Electronic Building Block (PEBBs)
- Developed with the US Office of Naval Research
- IGCT Technology



The PEBB is a standardized module that allows rapid configuration of power converters to meet specific customer needs, including:

- **AC - DC conversion**
- **DC - AC conversion (1 or 3 phase)**
- **Frequency changers**
- **DC - DC voltage changes**

Frequency Changers (FC)

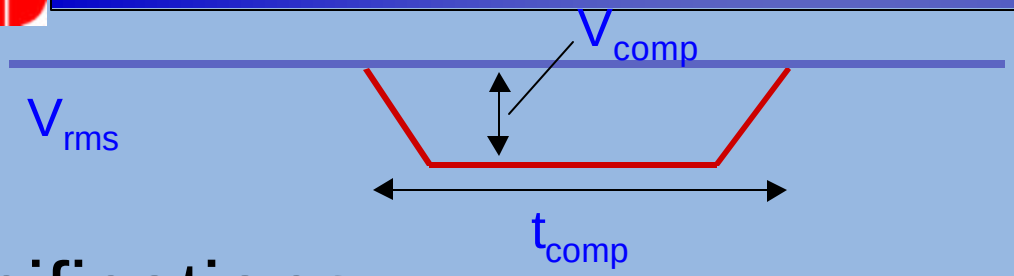
- Railway systems are the most common applications
  - Many rail systems operate on frequencies lower than 60 Hz.
  - Railway is actually a large single-phase load
  - Three-phase to single-phase frequency converter provides required frequency for the load and balances the load for the utility

- DB Energie (Germany)
  - 50Hz 3-phase to 16.67Hz 1-phase
  - New 175mph high-speed line
  - Inauguration Spring 2002
  - 11 units ordered to date

Dynamic Voltage Restorer (DVR)

- Medium voltage (e.g. 13.8 kV)
- In series between source and protected load.
- Protects loads from momentary voltages sags (not outages) by replacing “missing” voltage
- Facility level protection
- Potential customers:
  - Semiconductor plants
  - Automotive manufacturing
  - Plastic extrusion process
  - Paper mills
  - Petro-chemicals
  - Pharmaceuticals
  - Glass Manufacturing
  - Textiles Industry

Dynamic Voltage Restorer (DVR)



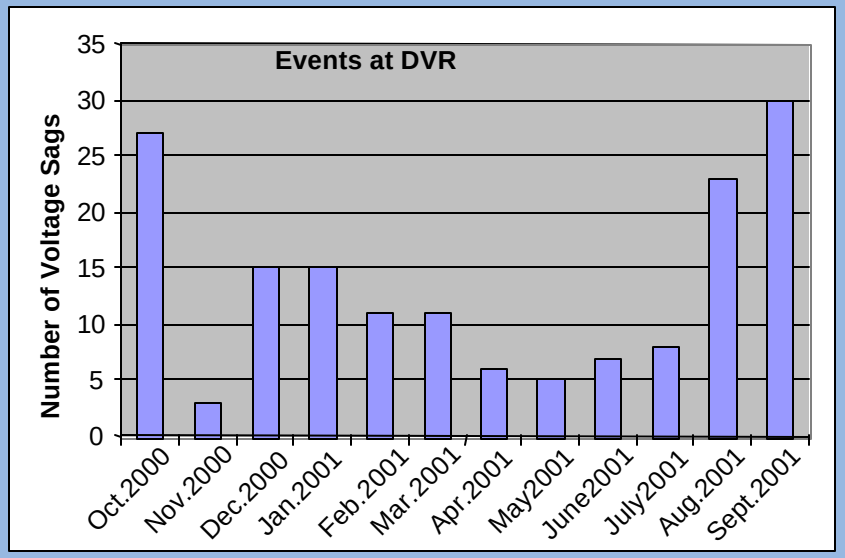
Specifications

- 3-phase sag compensation (V_{comp}) 35%
- 1-phase sag compensation (V_{comp}) 50%
- Compensation duration (t_{comp}) 0.5s
- Protection level facility
- Connection voltage (typical) 13.8kV
- Protected load power 10-25 MVA

Dynamic Voltage Restorer (DVR)

Surfa e
Platfo

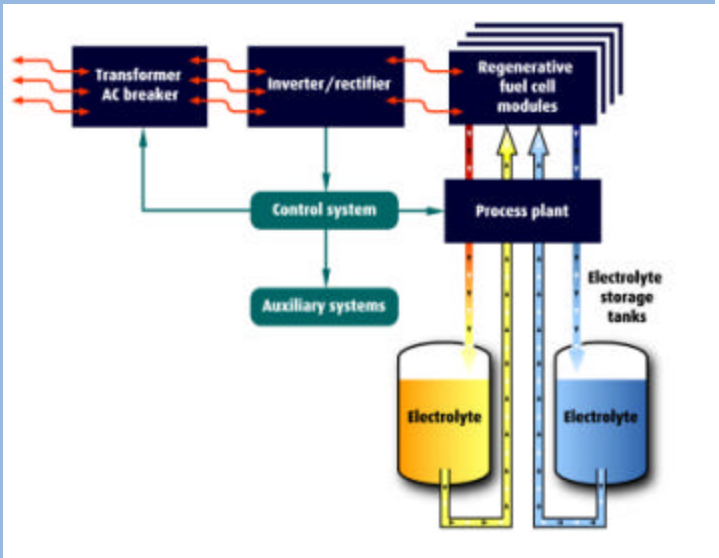
Chip Manufacturing Plant



DVRs installed:	2 units, 22 MVA each
Events per year:	~150
Estimated costs per disturbance:	up to $1 million
Total saved outage costs per year:	**~$20 million**
Turnkey cost:	**< $12 million**

Regenerative Fuel Cell (RFC)

Regenerative Fuel Cell (RFC)



- Regenerative Fuel Cell (RFC)
  - Used as a base load continuous energy source.
  - "Pumped storage" capability without physical constraints (hydro/air).
  - Stores energy to take advantage of daily load cycles.
  - Ability to provide real & reactive power.
  - Environmentally benign, low noise, small footprint (100 MWh on 2 acres).
- Potential Customers:
  - Large industrial or commercial loads.
  - Campus-like loads, i.e. air force base.
  - Utilities looking for solutions for their customers - i.e. TVA buying for air force base.

Regenerative Fuel Cell - TVA

TENNESSEE VALLEY AUTHORITY

TVA to Build Innovative Power Storage Plant in Mississippi

October 15 , 2001

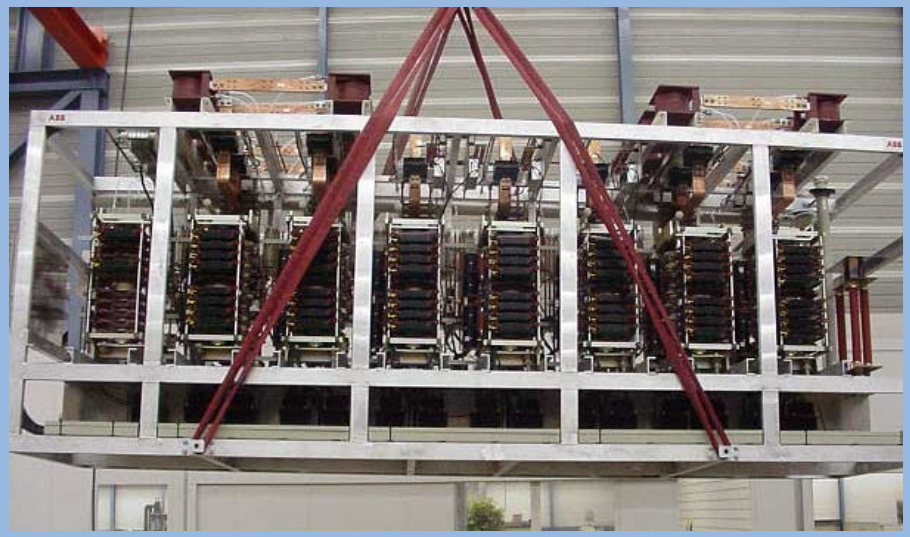
COLUMBUS, Miss. — TVA today officially launched construction of the nation's first large-scale, battery-like power storage facility that will store electricity during off-peak periods and retrieve it for use when the need for power increases.

A groundbreaking ceremony was held in Columbus, where TVA is planning to introduce the new technology in the United States on a site near Columbus Air Force Base. The energy storage project will cost in excess of $25 million and is expected to begin operation in 2003. ...

"This project will generate value for our customers by reducing the need for high-cost generation during times of peak use," said TVA Director Skila Harris. "It also helps us make more efficient use of available resources, demonstrating TVA's commitment to excellence in business performance and public service." ...

www.tva.gov/news/releases/1001storageplant.htm

Combined chopper & inverter
2 x 15 MW / MVA



Power Quality for Columbus AFB Mississippi

Delivery
2002

BESS - Golden Valley Electric

Problem

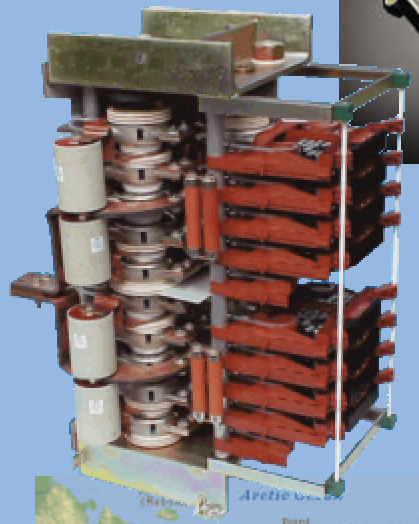
- System disturbances caused customer interruptions

Solution

- Turnkey 40 MW battery energy storage system to provide rapid response to system disturbances
- Global consortium led by ABB with batteries from Saft AB

Benefits

- Avoids need for spinning reserve or expensive system enhancements
- Provides voltage support during normal operations and back-up energy during system disturbances



BESS - Golden Valley Electric

Surface & Platforms

www.gvea.com/Projects/bess.htm

Customer Services | About GVEA | Current Projects

- Alternative Energy
- BESS
- Bradley Lake
- Healy Clean Coal
- Northern Intertie
- Project Archive
- Contact Info

Battery Energy Storage System (BESS)

On October 10, Golden Valley Electric signed a $30 million contract with ABB Power Systems to construct the co-op's Battery Energy Storage System (BESS). The BESS will be housed at GVEA's North Star Terminal building on Bidwell Avenue, and when operational, will provide 26 megawatts of backup power to GVEA's system for 15 minutes.

"The BESS is one part of the Northern Intertie Project and will be the largest battery project in the world. We estimate that our members will see a 70% reduction in power supply outages - outages due to generation and transmission problems," says GVEA president & CEO Steve Haagenson.

The BESS will be composed of 13,760 high performance nickel-cadmium battery cells and when complete, will increase reliability on the cooperative's system. Construction is expected to begin before the end of this year and the BESS is scheduled to be operational during the summer of 2003.

Construction of the BESS is one of GVEA's initiatives to improve the reliability of service to Golden Valley members. When online, the BESS will automatically pick up 26 megawatts of load in the event of power plant or transmission line equipment failure. Fifteen minutes is long enough for the co-op to start up and bring local generation online. The switch from power line to battery and back to power line should be seamless and go unnoticed by members.

BESS benefits include:

- Capacity deferral
- Spinning reserves
- Reduced air emissions
- Improved reliability Power quality
- Reduced losses
- Lower risks from fuel price changes

World's Largest Battery Energy Storage System awarded to ABB / SAFT by GVEA, Fairbanks, Alaska

- Advanced Electrical Power Systems -

Summary

Overall Health of the Thrust

- People are excellent; not enough
  - Critical shortage of power experts worldwide -- even more so, US citizens.
- Facilities marginal; emerging new approaches require new facilities
- Applied research scope is severely limited by available funding and people
- Technical opportunities/Under supported S&T areas:
  - Thermal management
  - Stimulation/Simulation (hardware in the loop) analysis
  - Energy Storage
  - Superconducting and cryogenic systems -- reduce resistance
  - Soft-switching topologies & power dense motors (low speed high torque)
  - Thermal management materials
  - Insulating materials >13.8kV bus and high dV/dt
  - Superconducting and cryogenic materials and components
  - Pulsed power weapons -- devices and materials
  - Permanent magnet materials
  - Capacitors and Inductors

(Key Issues) Changes Required

- Funding, Education and a National Plan