Advanced Aeropower Technology

Integrated Power Management & High Efficiency Superconducting Electric Rotating Machinery

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Outline

- Overview of Institutions
  - FAMU-FSU College of Engineering
  - Center for Advanced Power Systems & Magnet Lab
- Relevant Experience and Related Activities
  - All-electric ship initiative (ONR)
  - Other CAPS programs
- Power Technology Component of URETI
  - Overall vision
  - Fuel cells
  - Integrated power management, new network topologies
  - Superconducting rotating machinery for reduced space and weight (aircraft application)

FAMU-FSU College of Engineering

HBCU, part of the Florida Public University System
~ 15,000 students

Research I university, part of the Florida Public University System
~ 35,000 students

- Off-campus for both universities
- All faculty with dual appointment
- Independent admission, math & science track, and degrees
- Full integration for engineering curriculum

FAMU-FSU COE by the numbers

- Founded in 1982
- 5 Departments ~ 2000 students (1700 undergrad, 300 grad)
  - Electrical Engineering: 600 (550 BS, 40 MS, 10 PhD)
  - Mechanical Engineering: 400 (300 BS, 50 MS, 50 PhD)
  - Chemical Engineering: 350 (300 BS, 30 MS, 20 PhD)
  - Civil Engineering: 350 (300 BS, 30 MS, 20 PhD)
  - Industrial Engineering: 300 (250 BS, 40 MS, 10 PhD)
- Engineering education for under-represented minorities
  - 55% African-American
  - 25% Women (over half African-American)
  - Breakdown by university:
    - BS: 45% FAMU, 55% FSU
    - MS: 25% FAMU, 75% FSU
    - PhD: 10% FAMU, 90% FSU
- ~ $15M/yr (about 1/3 Mech. Eng. alone) in direct research funding, plus access to extra funding and collaborations through affiliated research centers

Affiliated Centers (Partial List)

FAMU-FSU College of Engineering

National High Magnetic Field Laboratory
- Magnet Science & Technology
- Condensed Matter Physics
- $30M/yr funded mostly by NSF

Center for Advanced Power Systems
- Power Engineering
- Superconductivity and Power Tech.
- $6M/yr mostly from ONR

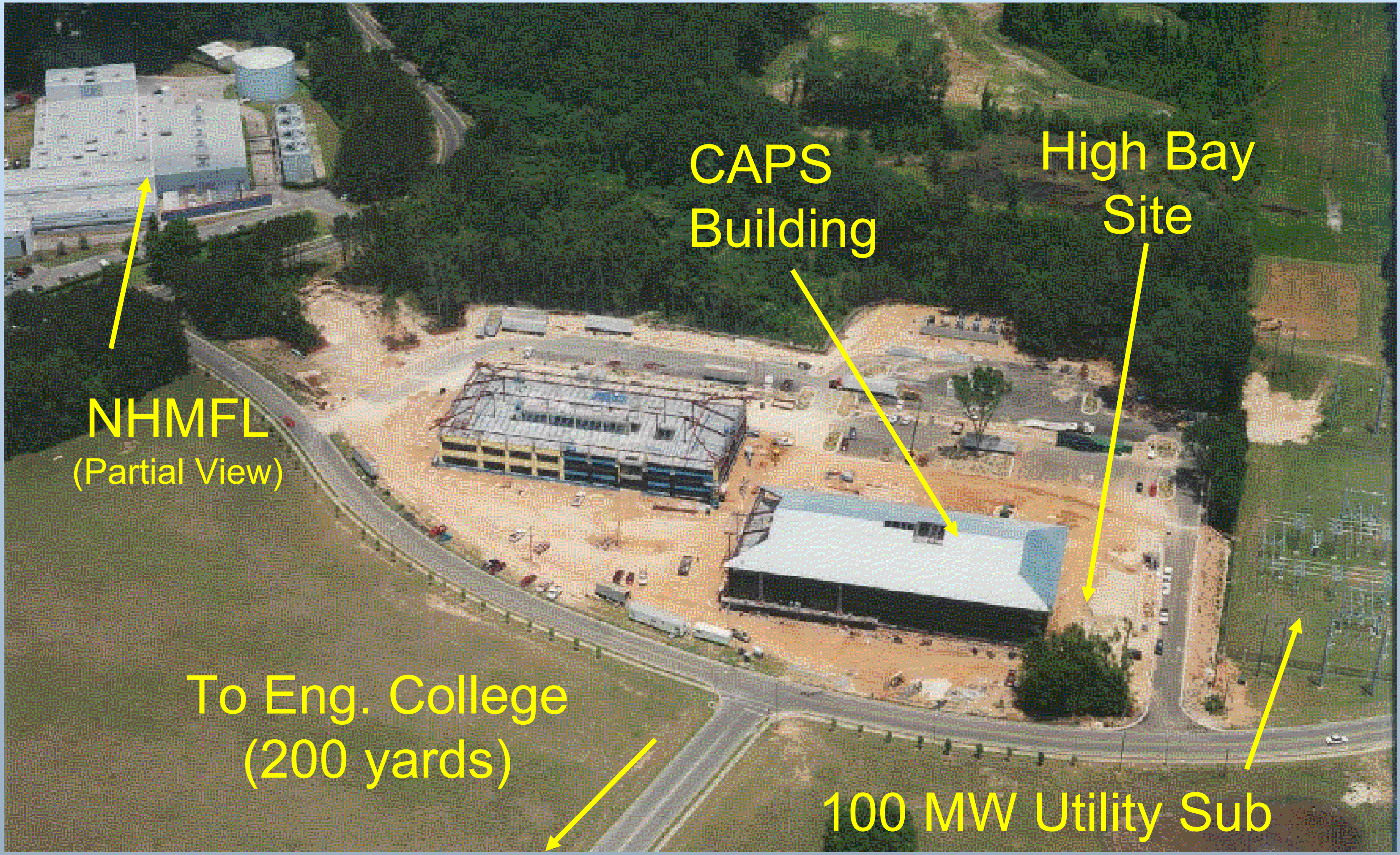
Materials Research & Technology
- Basic materials research
- $2M/yr mostly from the State of Florida

National High Magnetic Field Laboratory

CAPS (Center for Advanced Power Systems)

- Established in 2000 with grant from ONR as part of all-electric ship initiative, with the following goals:
  - Lead the resurgence of interest in power engineering
  - Establish a world class research center and facility focusing on power system issues
  - Develop a world class engineering education program
    - Undergraduate
    - Graduate
    - Continuing
  - Establish wide spectrum of interactions
    - Government – Federal, DOD, DOE – State
    - Industrial – Military and Commercial
    - Academic – Other Universities
  - Be a National Center for Power Engineering Research

CAPS Facilities



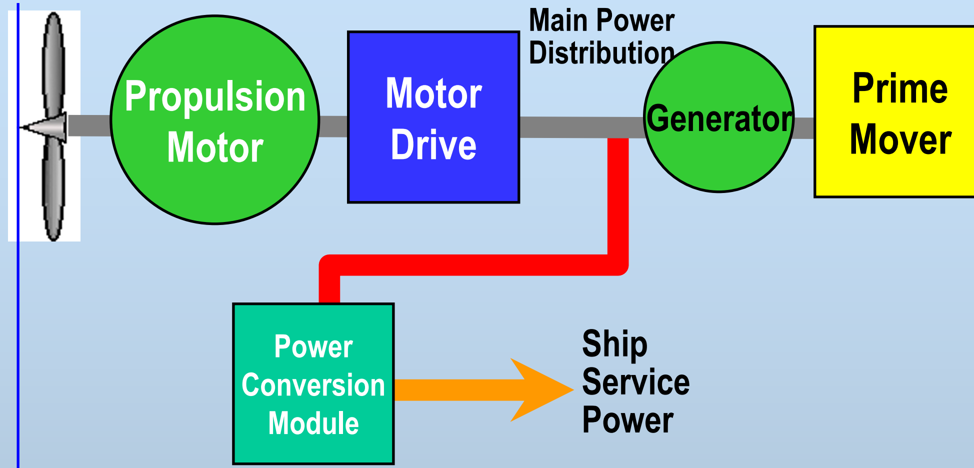
CAPS Research Infrastructure

- New Building
  - Site in Innovation Park, Tallahassee, between substation and NHMFL, near engineering school
  - Completion 12/31/02
    - Offices occupied 1Q/03
    - Phase I of test facilities complete 3Q/03
  - Space
    - Office - for 48 persons - 10,000 SF
    - Classrooms – 4,000 SF
    - Labs - 10,000 SF
    - High Bay Area - 4,000 SF
    - Yard space – 14,000 SF
    - Total Program Area – 40,000 SF (approx.)
  - All necessary infrastructure to establish a power engineering program

Electric Ship Concept

Definition

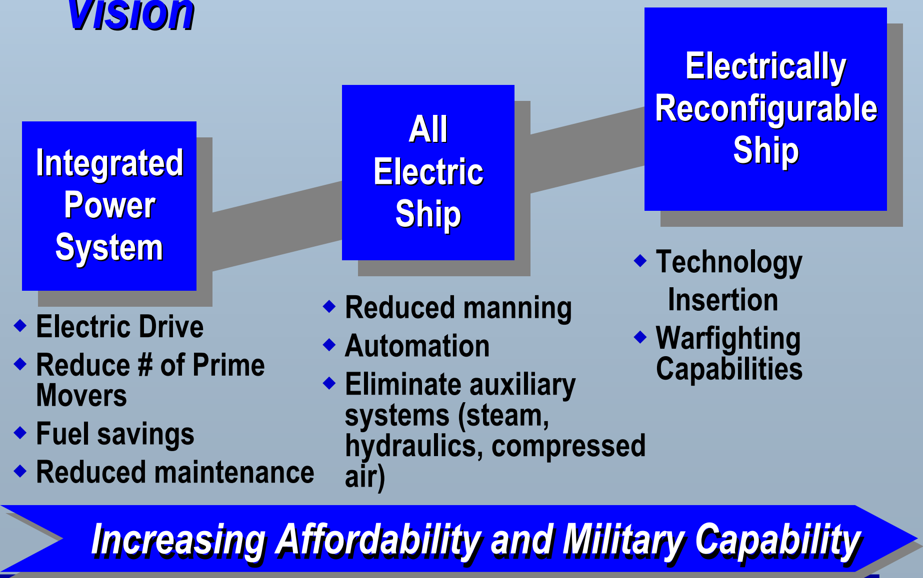
Ship electric power system which integrates power generation, electric propulsion, ship service distribution, combat systems support, and power management



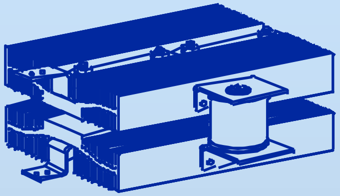
Why Integrated Power Systems?

- Warfighting Improvements
  - Rapid Reconfiguration of power
  - Enables advanced pulse-power weapons
- Reduced Cost
  - Improved fuel economy from more efficient loading
  - Reduced manning from reduced prime movers
- Reduced Noise
  - Eliminates gear (motor noise is lower level and better controlled)
  - Enables lower speed propellers
- Naval Architecture Flexibility

Vision



Key All-Electric Ship Technologies

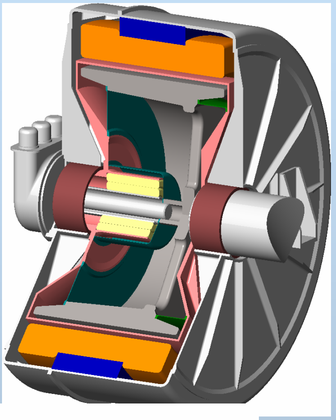


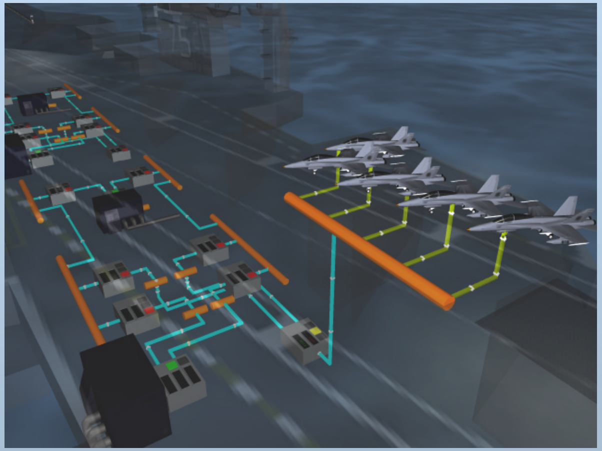
Power Electronics

- Reduces cost
- Increases power density

Advanced Motors (incl. s/c)

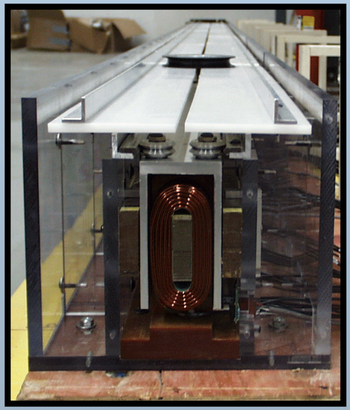
- Increases power density



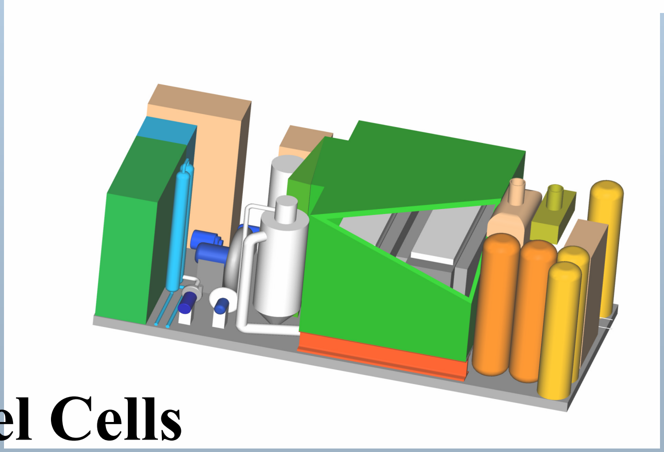


System Modeling

- Integration
- Controls



Advanced Linear Motor



Fuel Cells

- Fuel efficiency
- Reliability

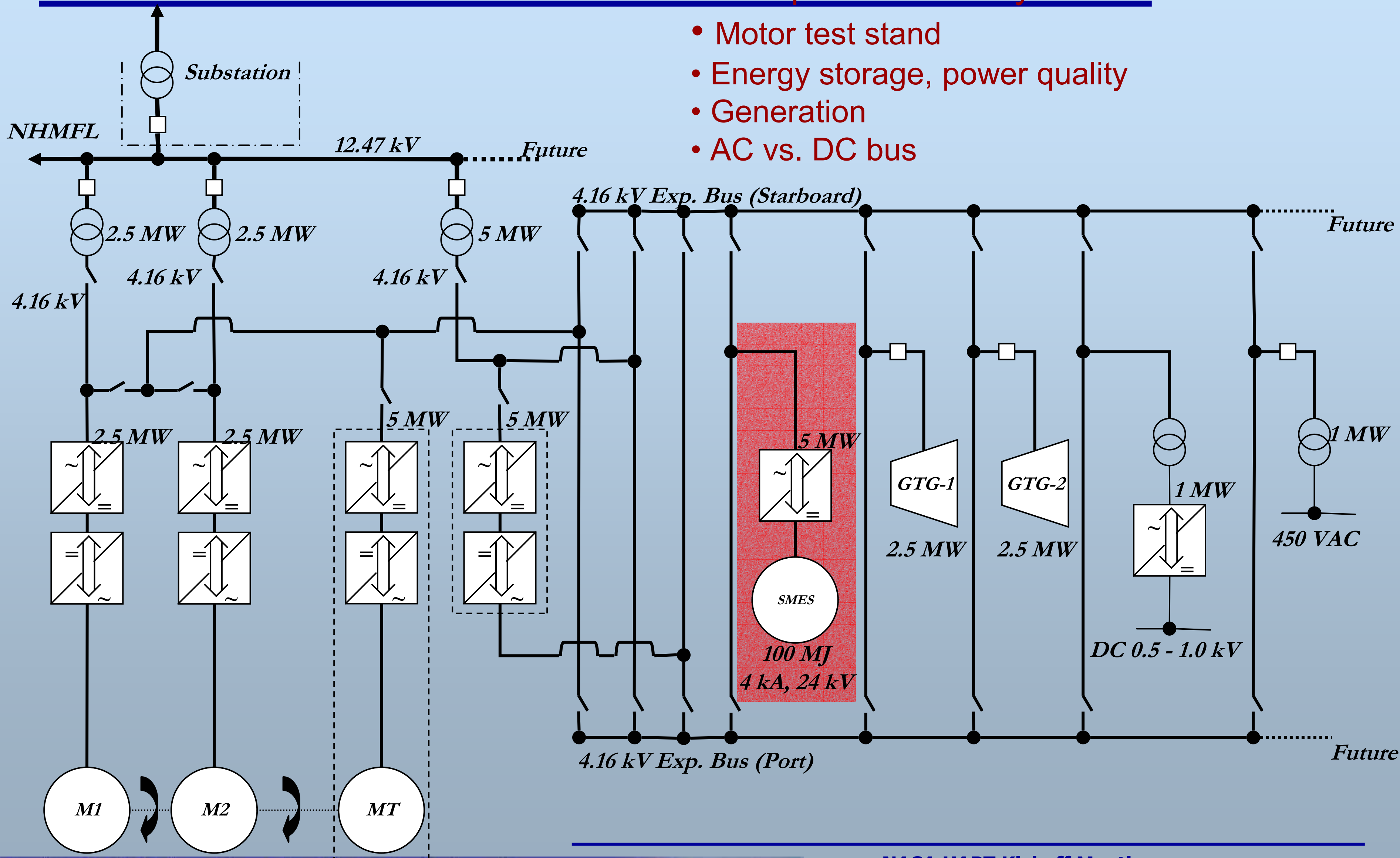
CAPS: Areas of Work

Major Initiatives and Research Programs

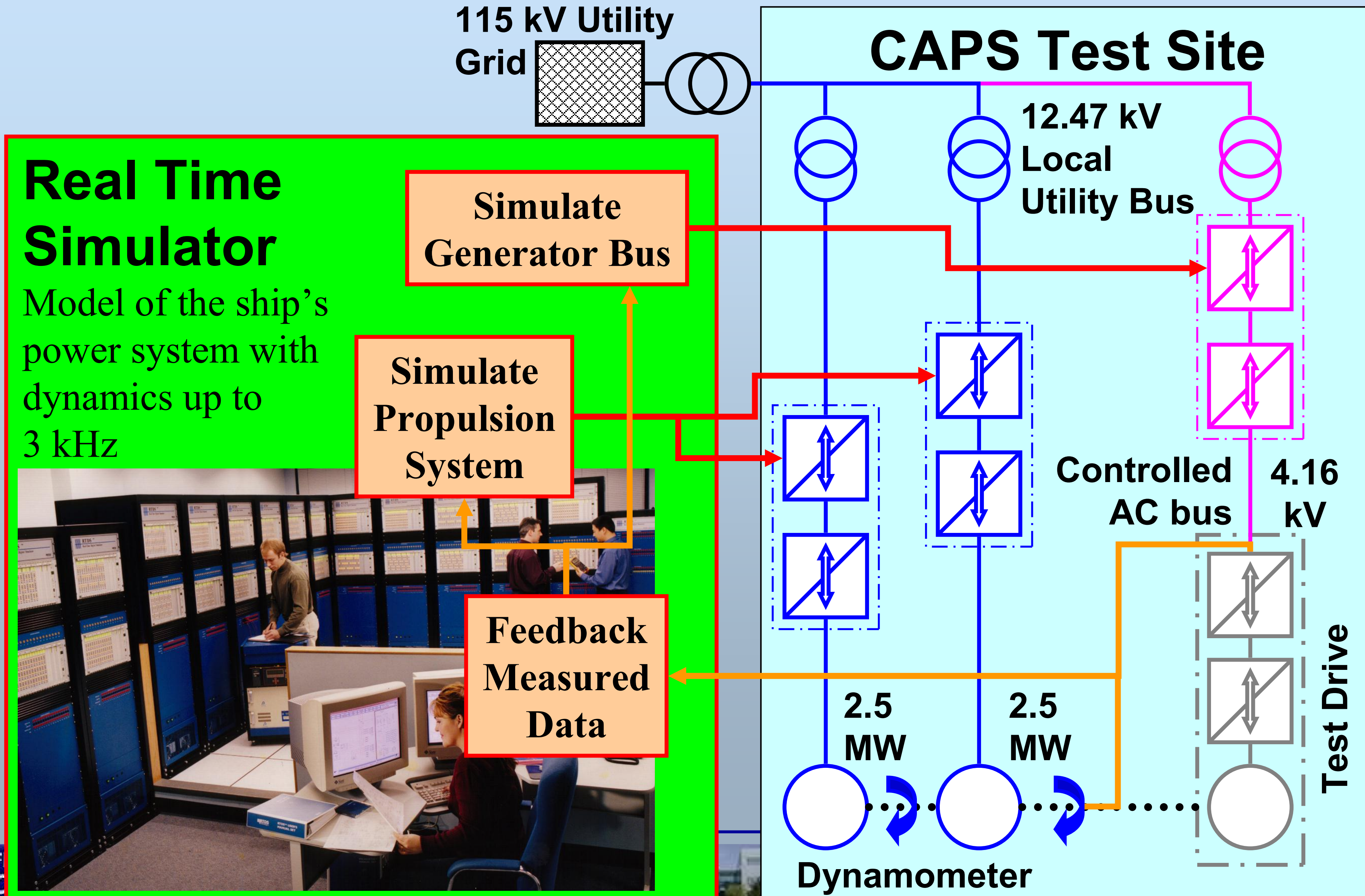
CAPS Test Bed Facility

A complete 'island' system rated at 5 MW

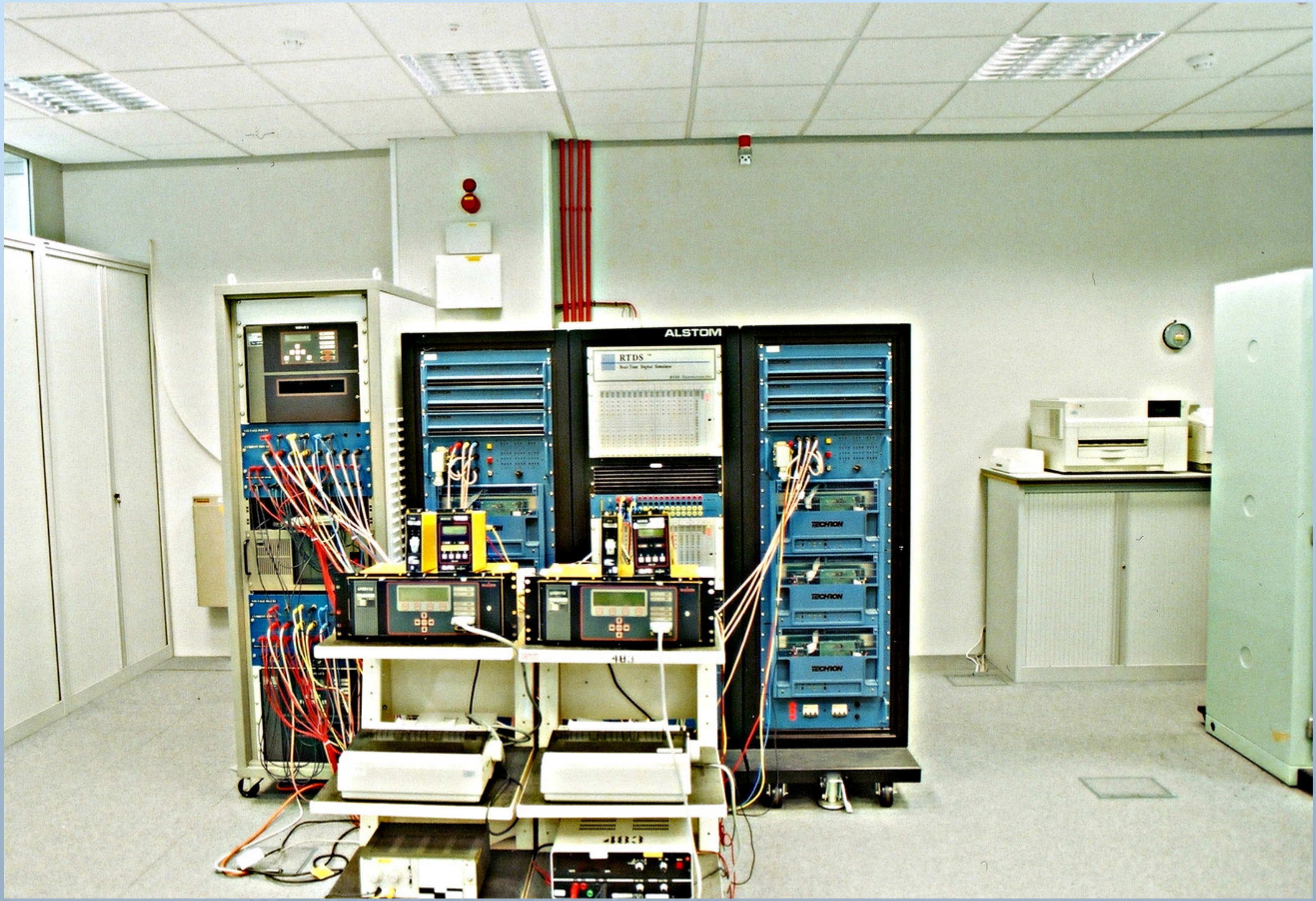
- Motor test stand
- Energy storage, power quality
- Generation
- AC vs. DC bus



Commissioning @ CAPS: Hardware in the Loop Simulation

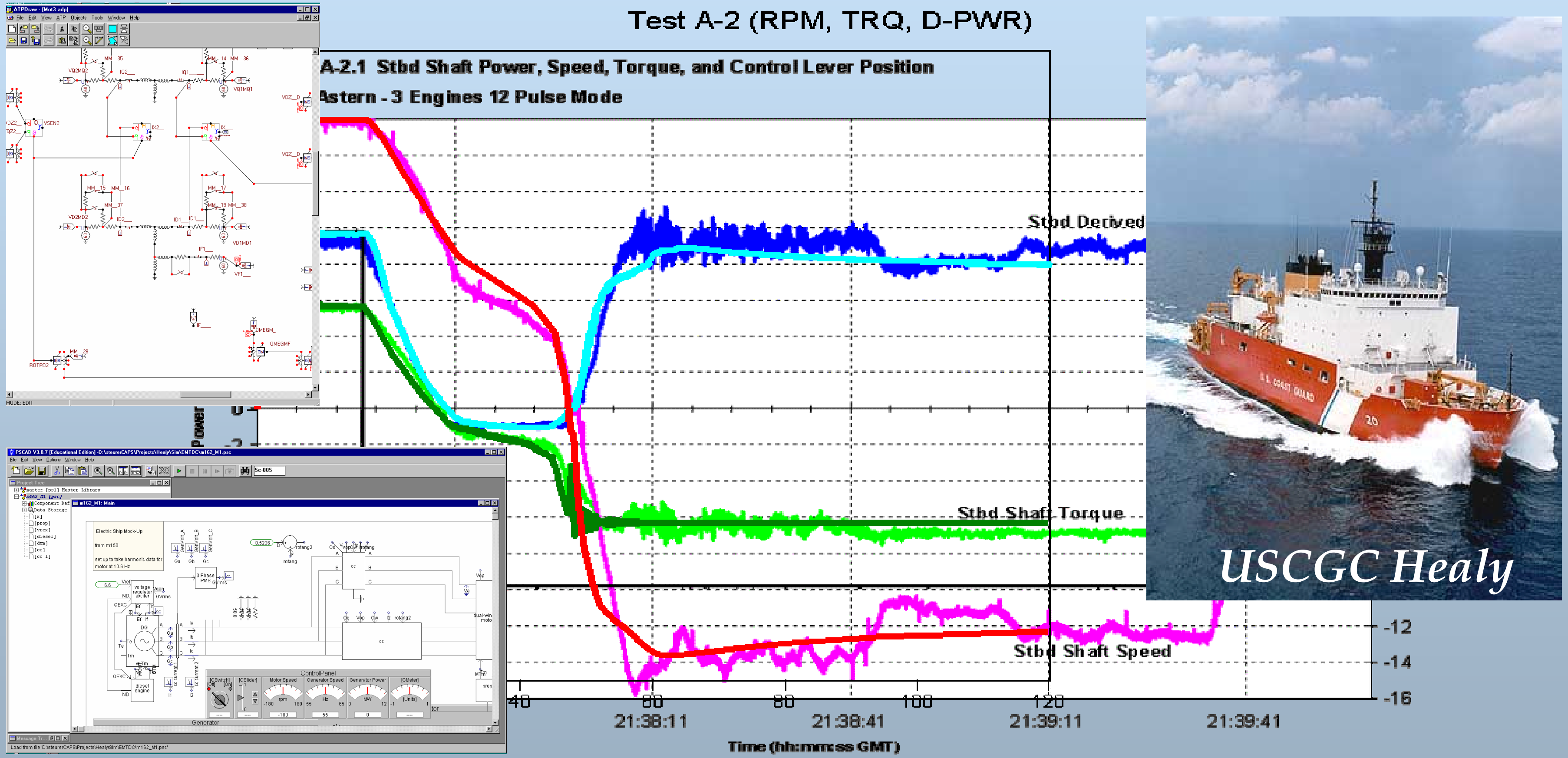


RTDS linked to relays



Current Work: Healy Project

Existing Software ⇔ **Operational Ship**



Capability for Simulating Marine Propulsion Systems

URETI Activities

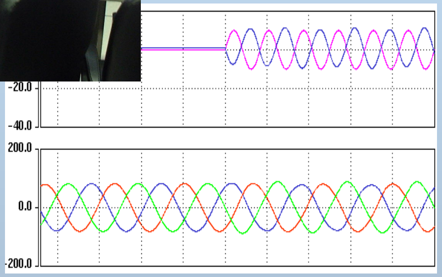
Integrated Power Management

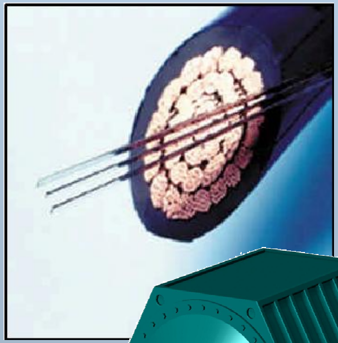
&

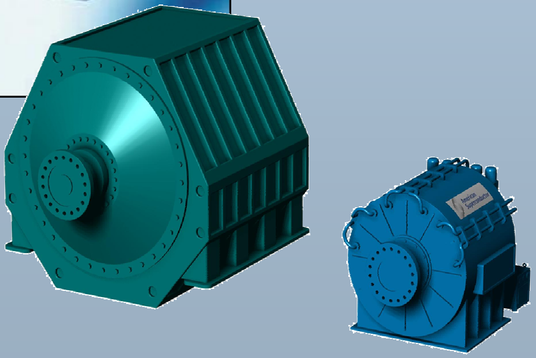
High Efficiency Superconducting Electric Rotating Machinery

Power-related activities @ FAMU

- Integrated Power Management
  - Study relevant power network architectures
  - Apply real-time digital simulator to aircraft power systems
  - Trade-off studies
  - Integration of new technologies (e.g., fuel cells)
- High Efficiency Superconducting Electric Rotating Machinery
  - Concurrent effort on all-electric ship
  - Reduced volume and weight for electric motors







Integrated Power Management
Electrical Network Architecture

- Objectives
  - Examine the impact of distributed generation, automatic reconfiguration (damage control), power electronics, and superconductivity on aircraft power systems
  - Provide simulation capabilities to examine the performance of individual components and control strategies
  - Provide input to guide fuel cell development efforts to better match optimum electrical network configuration
- Relevance/Impact
  - Increased reliability, safety, and performance through redundancy and reconfigurability
  - Provide platform for testing new concepts and technologies for power distribution networks applicable to aircraft

Integrated Power Management
Electrical Network Architecture

- Activity Leader: Dr. Tom Baldwin, Assistant Professor, Electrical Engineering
- Level of Activity:
  - Research Associate/Post-Doc: 1 @ 50%
  - Graduate students: 1 @ 100%
  - Undergraduate students: 2 @ 100% (summer only)
  - Undergraduate students project: 1 project team per year
- First Year Activities and Deliverables:
  - Model the electrical system architecture of a small aircraft (e.g., Gulfstream jet) on the real-time digital simulator system
  - set up evaluation criteria and procedures to proceed with modeling of larger aircraft, or for trade studies on small systems

Integrated Power Management
Proposed Approach (I)

- Leverage experience gained with USCG Healy project to develop model of aircraft electrical network using existing tools (technology cross-fertilization)

- Examine alternative system configurations using real-time digital simulation (RTDS)
  - model a base-line electric power system for the specified aircraft on the real-time digital simulator
  - create alternative designs of the power system and perform a comparison analysis (i.e. distributed generation and energy storage)
  - Establish requirements for fuel cell development applicable for aircraft application

Integrated Power Management
Proposed Approach (II)

- RTDS modeling of power system of a small aircraft
  - Start with small aircraft (e.g. Gulfstream jet)
  - Future modeling involving more complex systems (larger aircraft)
- Conduct technical trade-off studies
  - Integration of fuel cells as an alternative power source
    - Impact of replacing APU with fuel cells
  - Performance analysis based on:
    - AC vs. DC
    - Voltage level
  - Sensitivity analysis of power system parameters

Integrated Power Management Proposed Approach (III)

- Study aircraft electrical system architecture
  - validate simulation software for design applications by modeling an existing small aircraft to compare simulations with actual data
  - identify simulation and modeling problem areas and define further development needs
  - model the power system and controls on the RTDS
  - simulate failures and damage to the aircraft power system and analyze the system responses and ability to restore power to critical flight systems

- Analyze the impact of new devices and technologies on performance
  - develop and insert RTDS simulator models for new technologies (i.e. fuel cell, superconducting machines and power electronics devices)

Advanced Aeropower Technology

High efficiency superconducting electric motor

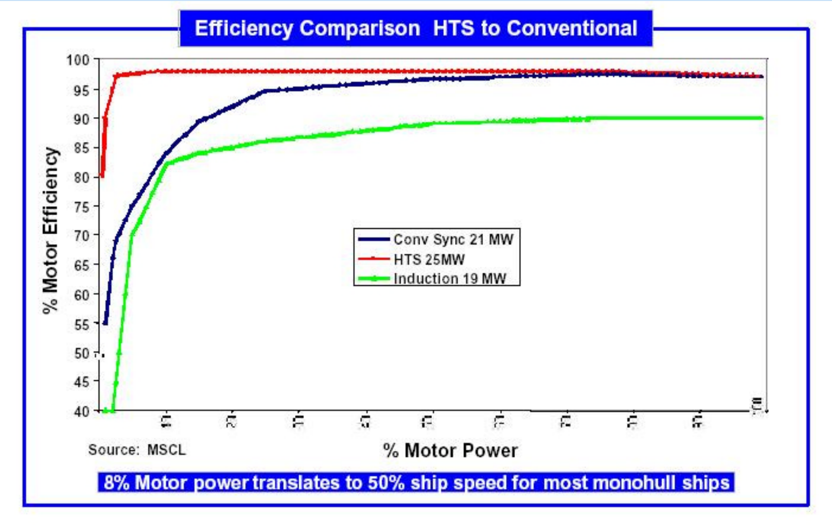
- Objectives
  - Establish targets for aircraft-based s/c motors
  - Develop s/c motor concepts to reach targets
  - Integrate to other technologies for new concepts of all-electric aircraft

- Relevance/Impact
  - Low weight/volume electric motors
  - Increased use of electrical actuators, elimination of mechanical/hydraulic systems
  - Enabling technology for all-electric aircraft concept

High Efficiency Superconducting Motor

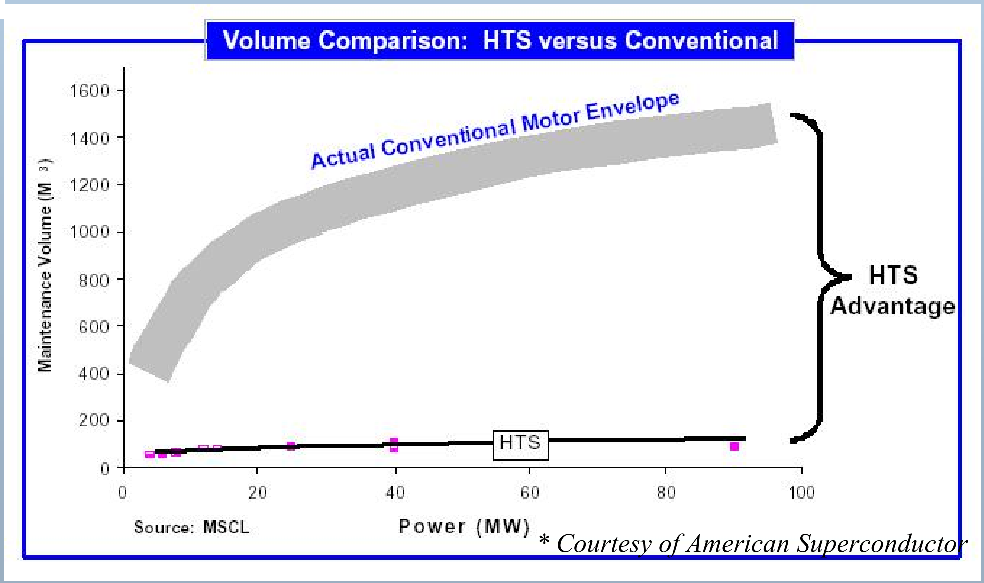
- Activity Leader: Dr. Cesar Luongo, Associate Professor, Mechanical Engineering
- Level of Activity:
  - Research Associate/Post-Doc: 1 @ 100%
  - Graduate students: 2 @ 100%
  - Undergraduate students: 2 @ 100% (summer only)
  - Undergraduate students project: 1 project team per year
- First Year Activities and Deliverables:
  - Survey of relevant experience for superconducting rotating machinery in the power range of interest
  - Develop database of material properties and technology status for the development of an s/c motor design
  - Establish targets for development program and design envelope for future tasks

Why superconducting motors?



Efficiency

Volume/Weight



* *Courtesy of American Superconductor*

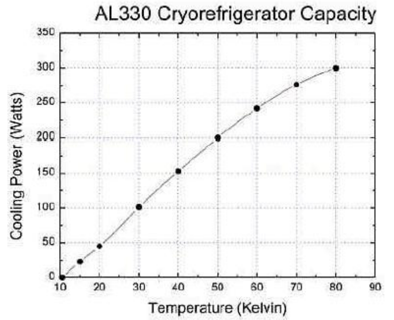
Challenge:

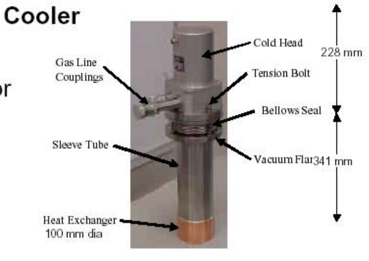
To extend size advantage to lower power ratings (relevant to aircraft application)

Enabling technologies

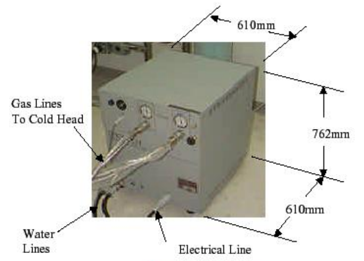
High Capacity Single Stage GM Cooler

- Wire cost/performance optimization suggests operating with a winding temperature of 20-40K for most motor applications.
- Gifford McMahon cryocooler output at 30 K has improved by nearly a factor of 4 over the past 5 years.
- MTBF of similar GM coolers exceeds 9 years





Cold Head



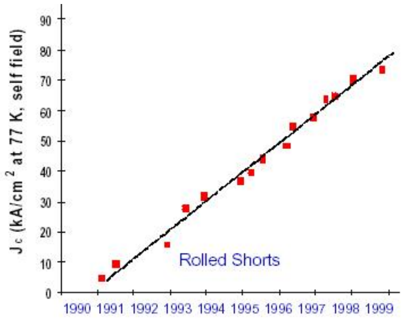
Compressor

Cryocoolers

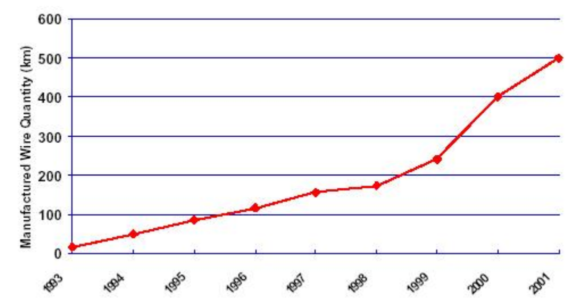
HTS superconducting wire

HTS Wire

Multifilamentary Bi-2223 Wire Progress at AMSC



High Performance Tape Creates Manufacturing Capacity



* *Courtesy of American Superconductor*

Increasing Availability and Performance

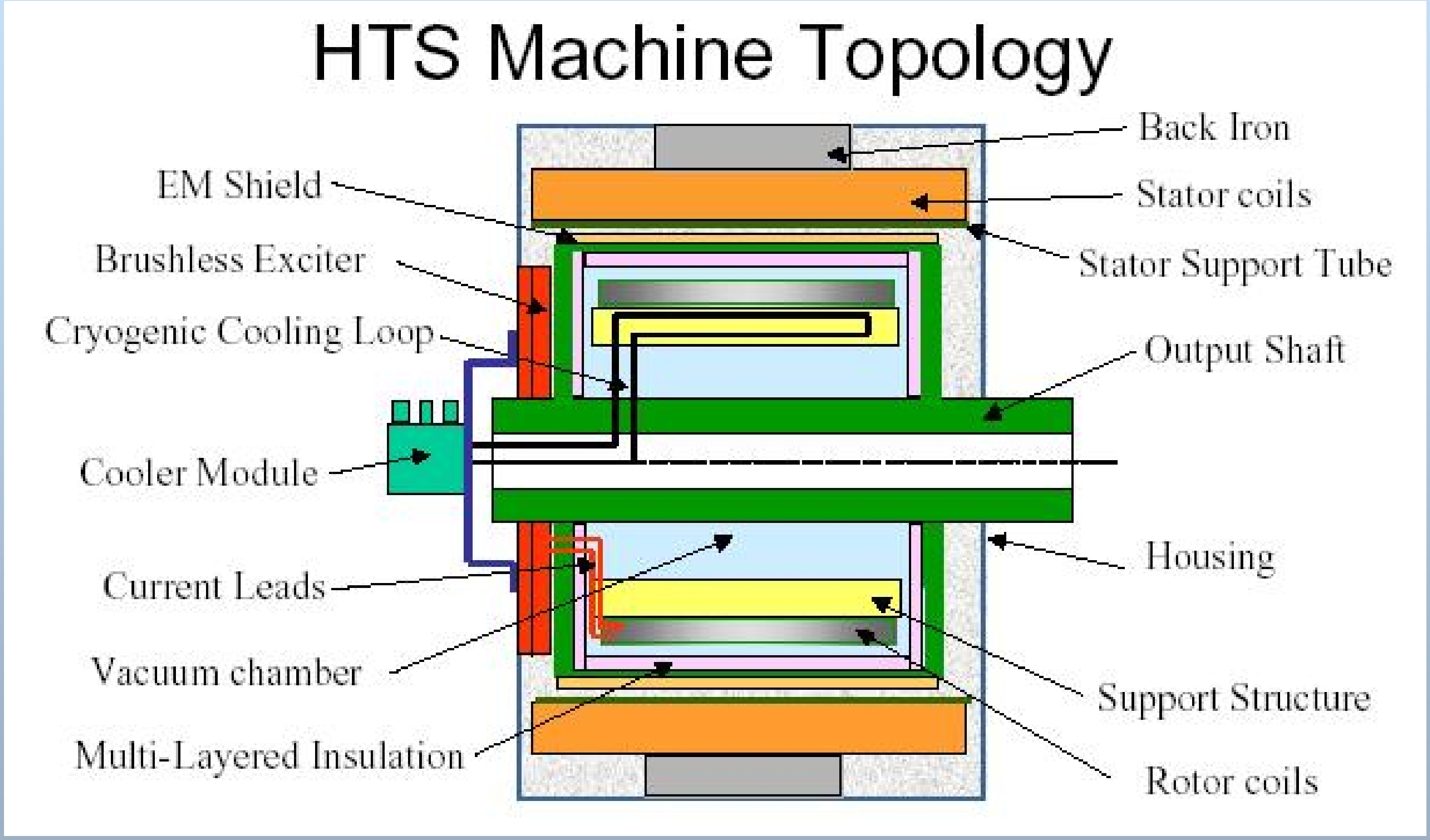
Challenges:

Integrate and take advantage of new technologies

Application of low AC-loss wire

Aggressive targets for operational parameters (high-B)

Notional design



** Courtesy of American Superconductor*

Superconducting Motors
Proposed Approach (I)

- Develop database of relevant material properties (superconductor, insulation, cryogenic, etc.) for the design of high-performance s/c motors
  - Benchmark state-of-the-art in all technical areas of relevance for a superconducting motor
    - HTS materials
    - Cryocoolers
    - Insulators
- Establish power rating targets for aircraft-relevant motors. Develop performance targets for s/c motor (power density, weight, etc.)
  - Evaluate prior experience
  - Assess potential gains in performance (weight, size, etc.)
  - Reconcile with program needs (system integration)

Superconducting Motors
Proposed Approach (II)

- Develop motor concepts capable of attaining targets. Perform trade-off to select most promising concept. Proceed with a detailed design of the s/c motor based on the preferred concept
- Integrate findings from this task to subtasks on electrical network architecture (Baldwin) and SO fuel cell studies (Parekh), as well as overall system integration tasks (Mavris)
- Determine best path for a prototype development program (sub-scale or full-scale), establish goals, schedule, and budget, and proceed with hardware demonstration program as resources allow

Ready to apply our resources and experience to advance the state-of-the-art of Aircraft Power Systems

Eager to be part of a great team

Georgia Institute of Technology

THE OHIO STATE UNIVERSITY

FAMU Florida A&M University

CWRU CASE WESTERN RESERVE UNIVERSITY

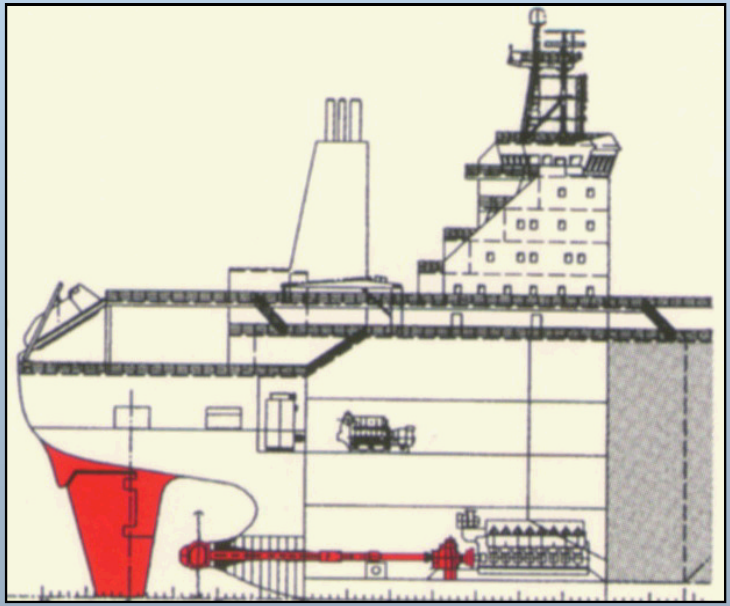
Back-Up Slides

Advantage: Design Flexibility

Alternative Propulsion Systems on 120,000 DWT Arctic Tanker

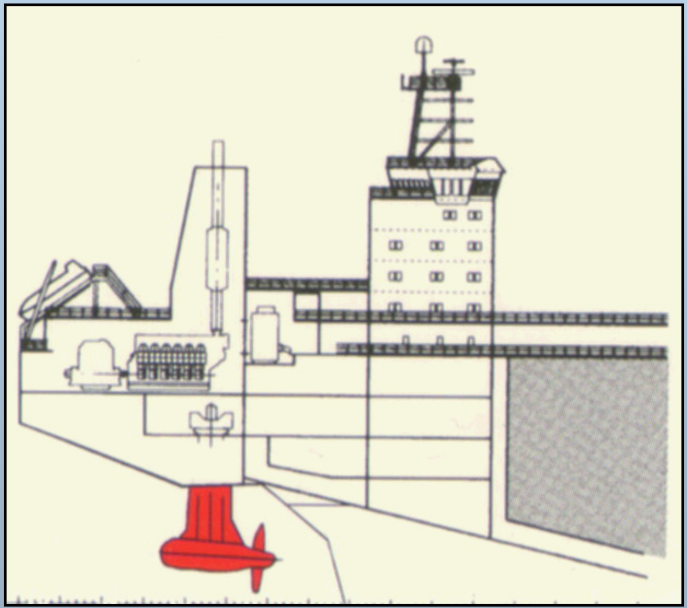
Diesel/Electric/Podded Propulsor
Allows Design Flexibility

Diesel/Mechanical Propulsion



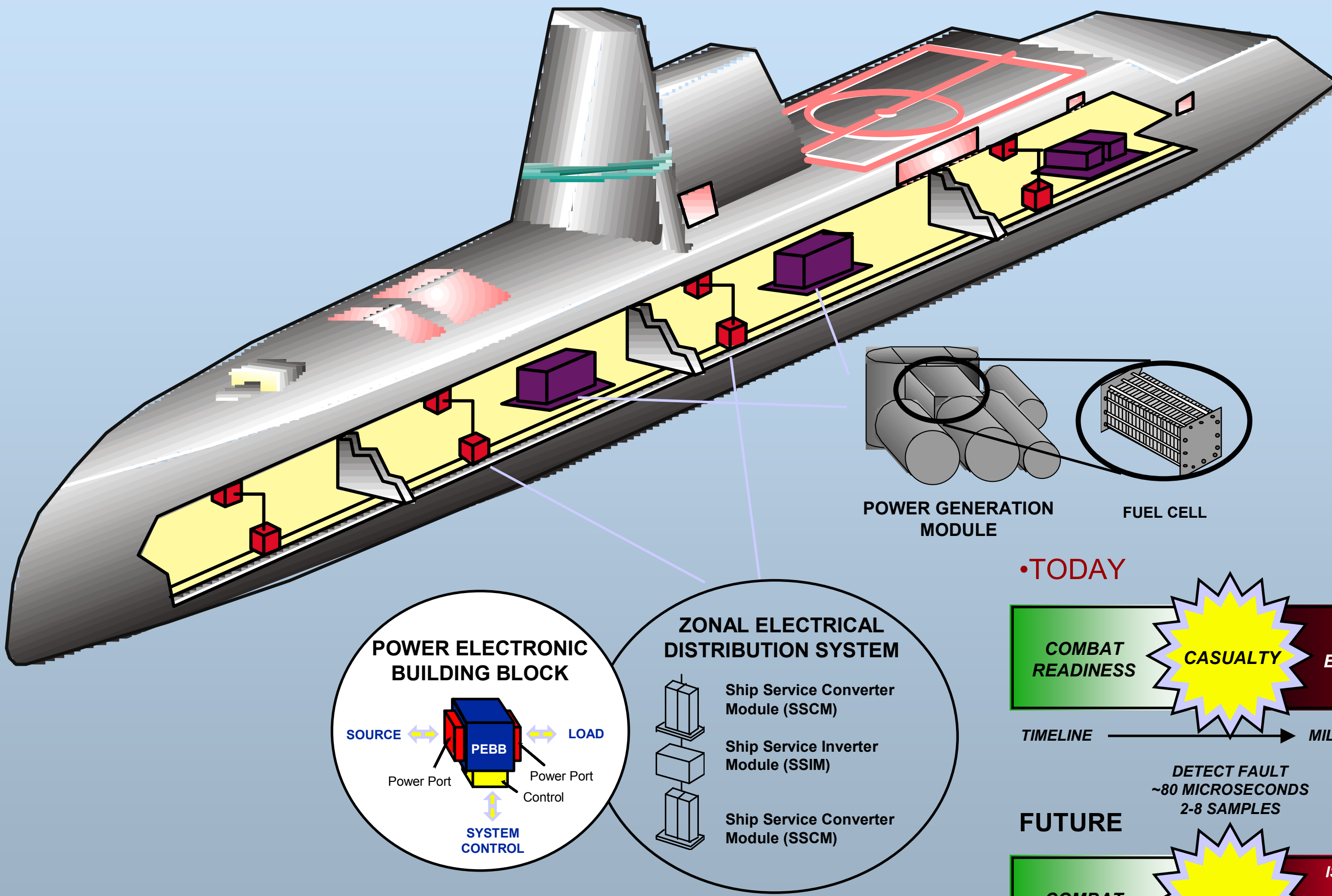
Courtesy, ONR

Diesel/Electric Propulsion



with Podded Propulsor

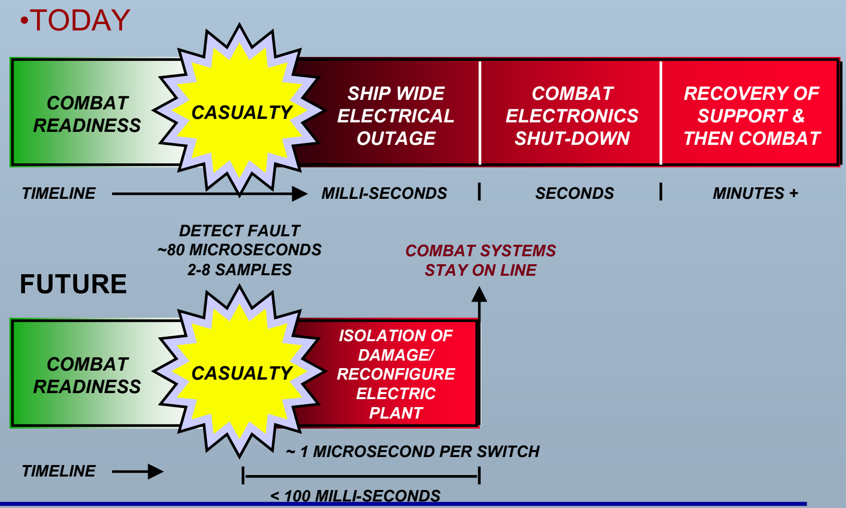
Advantage: Reconfigurable, Survivable Power System



POWER DISTRIBUTION MODULES

Challenges:

- ⇧ Power Density
- ⇧ Energy Density
- ⇧ System Efficiency
- ⇧ Resource Management and Control

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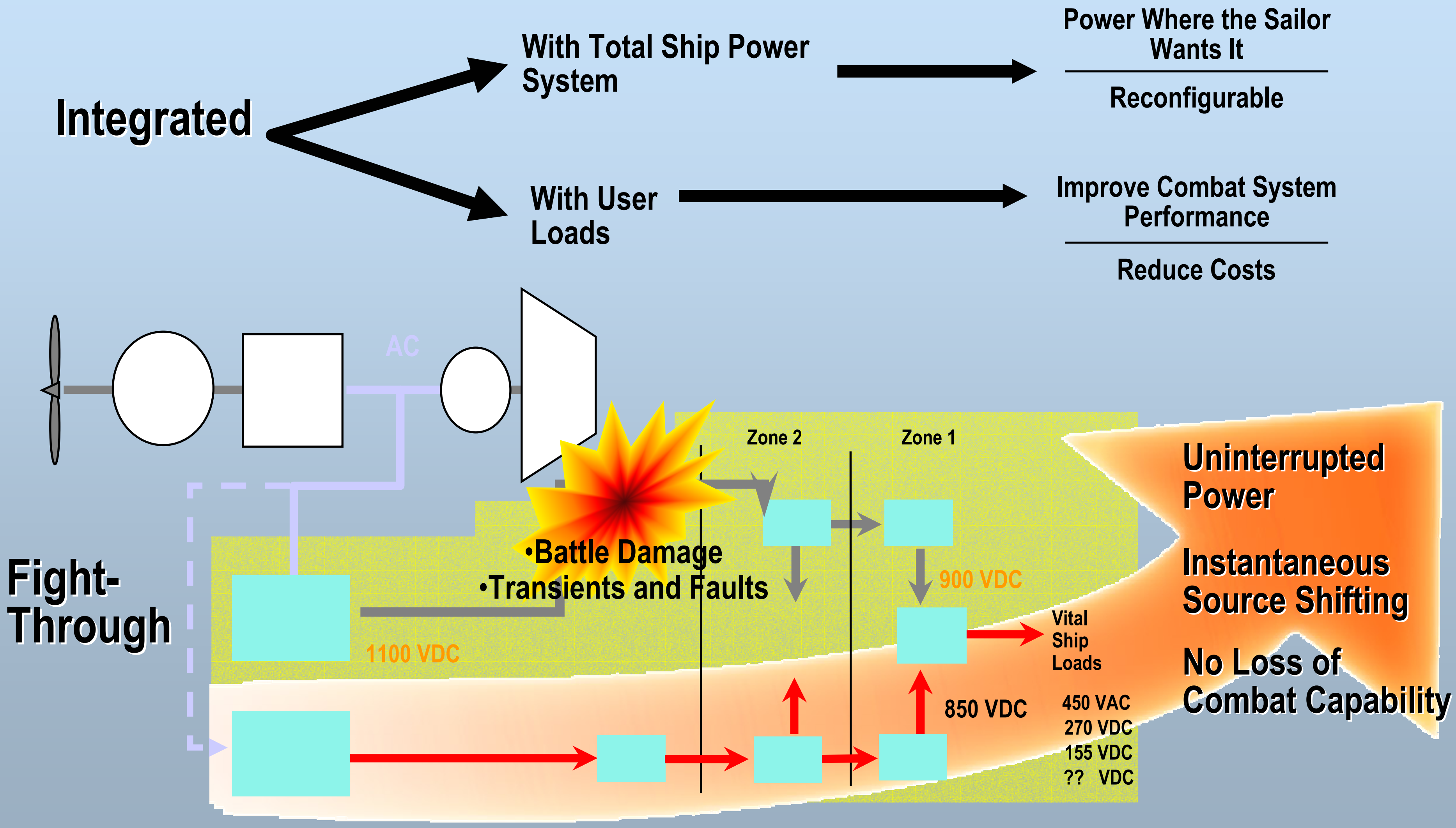
Integrated Fight-Through Power

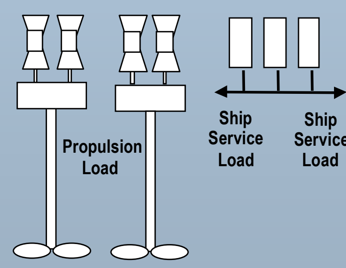


Advantage: Lower O&M costs

Next-generation destroyer (DDX)

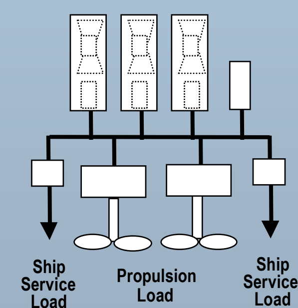
Next-generation carrier (CVX)

- Electric drive enables lower O&M costs:
  - Integrated propulsion and ship service power (fewer running prime movers)
  - Reduce fuel usage
  - Better match to total ship power requirements (fewer prime movers)
  - “Plug & Play” maintenance



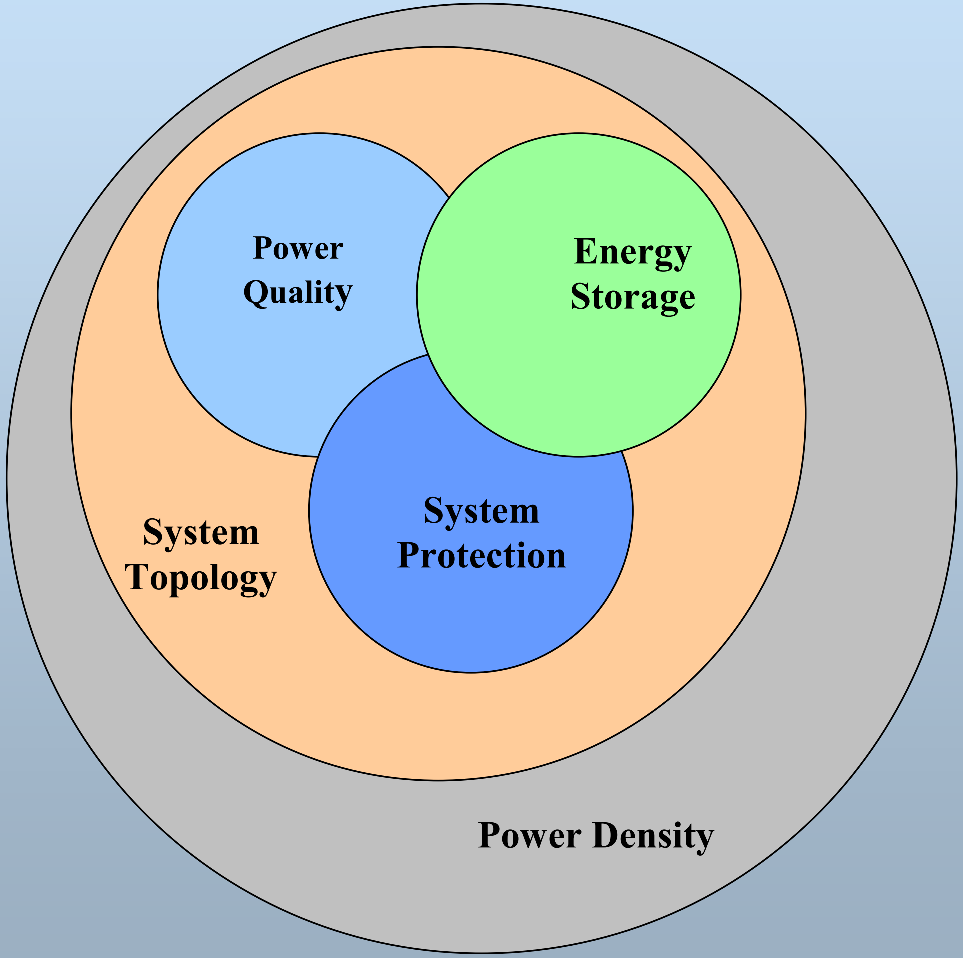
Segregated Power System 7 Prime Movers

or

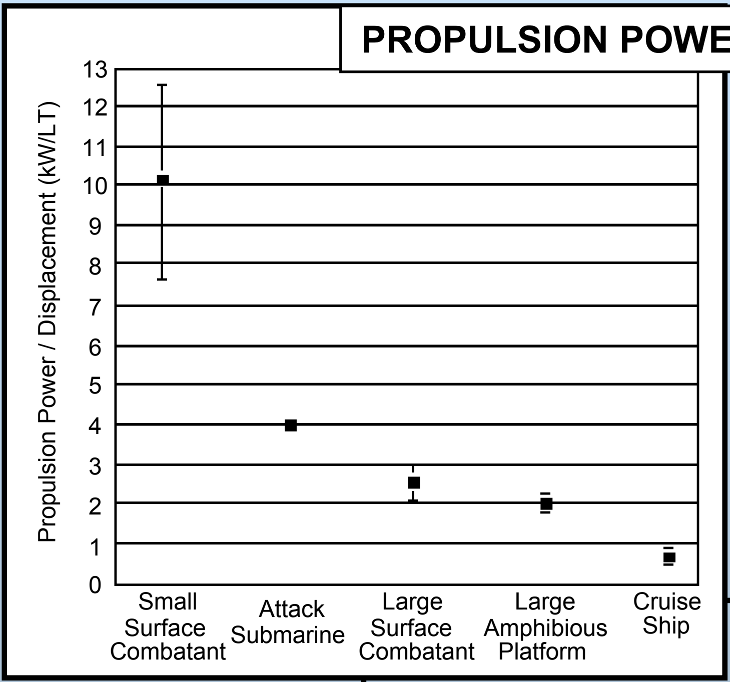


Integrated Power System 4 Prime Movers

Challenge: Power density



Challenge: Power Density (Navy vs commercial)

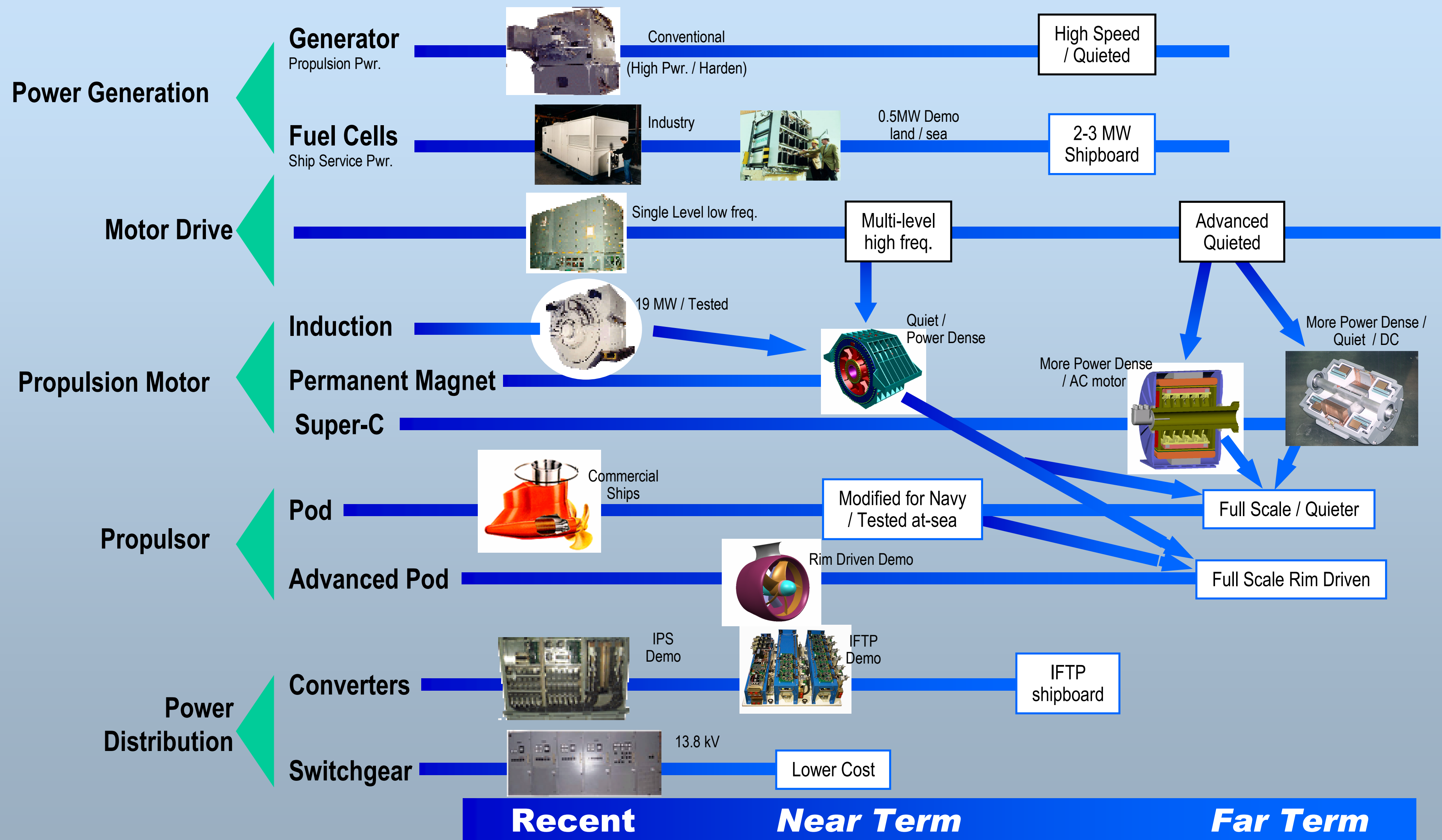


SHIP TYPE CHARACTERISTICS

		Small Surface Combatant	Attack Submarine	Large Surface Combatant	Large Amphibious Platform	*Cruise Ship*
Size	L (ft) B (ft) D (ft)	500 - 550 60 - 70 15 - 20	300 - 350 32 - 35 Diameter	900 - 1,000 125 - 135 35 - 40	500 - 650 65 - 85 18 - 22	*700 - 920* *100 - 120* *25 - 27*
Displacement	(long tons)	6,000 - 10,000	6,000	70,000 - 100,000	15,000 - 20,000	*45,000 - 55,000*
Propulsion Ship Service	(MW) 60 Hz (MW) 400 Hz (MW)	76 4 0.4	24 2 0.08	210 35 0.5	35 10 0.02	*24 - 42* *10 - 25* -
Prop RPM		CRPP 160 - 180	FPP <100	FPP 165 - 175	CRPP 160 - 180	*FPP* *150 - 190*
Prop.Power/Disp. (KW/LT)		7.6 - 12.7	4	2.1 - 3.0	1.8 - 2.3	*0.5 - 0.9*

FPP Fixed Pitch Propeller
CRPP Controllable Reversible Pitch Propeller

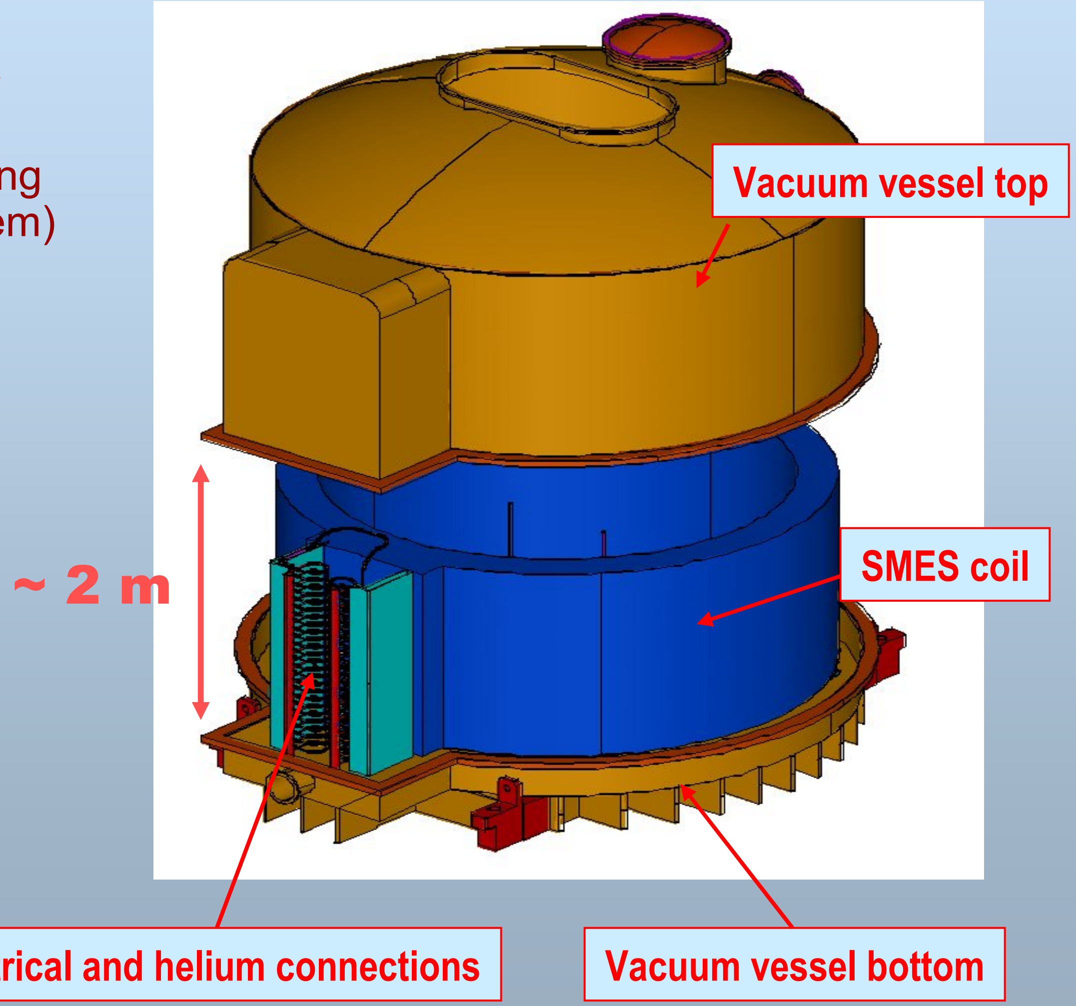
Potential Electric Warship Technology Areas



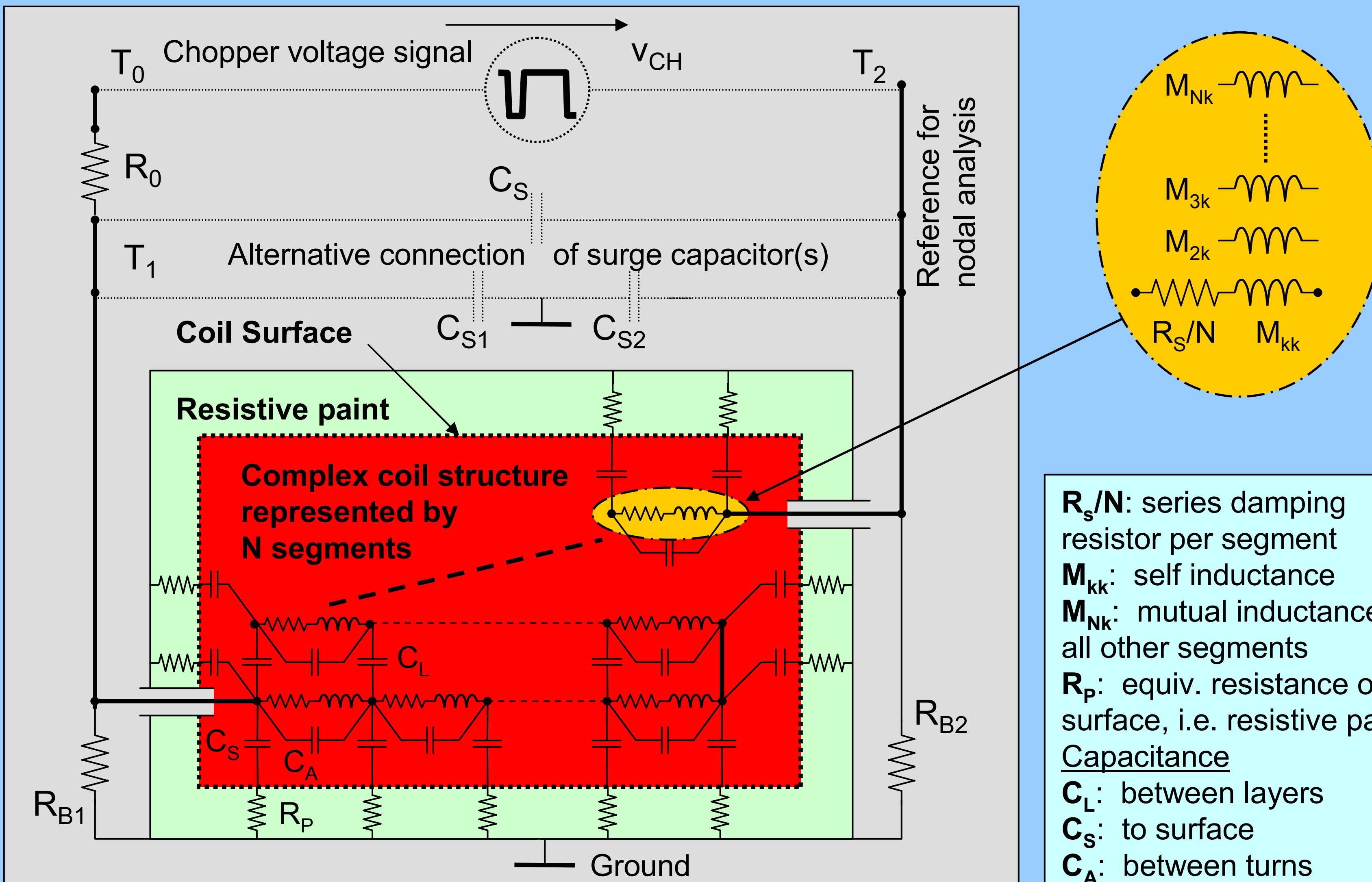
Under construction: 100 MJ SMES (Superconducting Magnetic Energy Storage)

- Magnet under construction
  - BWXT, Lynchburg VA
  - Expected completion 6/2003
  - Transported to CAPS for installation and commissioning (30 ton magnet, 35 ton system)
- Installation at CAPS
  - Vacuum vessel and cryostat
  - Refrigeration system
  - 5 MW power supply
- Commissioning and test
  - Operational in 2004
  - Pulsed operation and power quality demonstration
  - Research and education component

Expanded view of SMES system



Current work: Study of s/c coil-converter interactions



R_s/N: series damping resistor per segment
M_{kk}: self inductance
M_{Nk}: mutual inductance to all other segments
R_P: equiv. resistance of surface, i.e. resistive paint
<u>Capacitance</u>
C_L: between layers
C_S: to surface
C_A: between turns

USCG Ice Breaker Healy (all-electric): Electrical Network Simulation

- Length – 420 ft
- Maximum Beam – 82 ft
- Design Draft – 29 ft
- Displacement – 16,300 LT
- Four Sulzer Diesel Engines

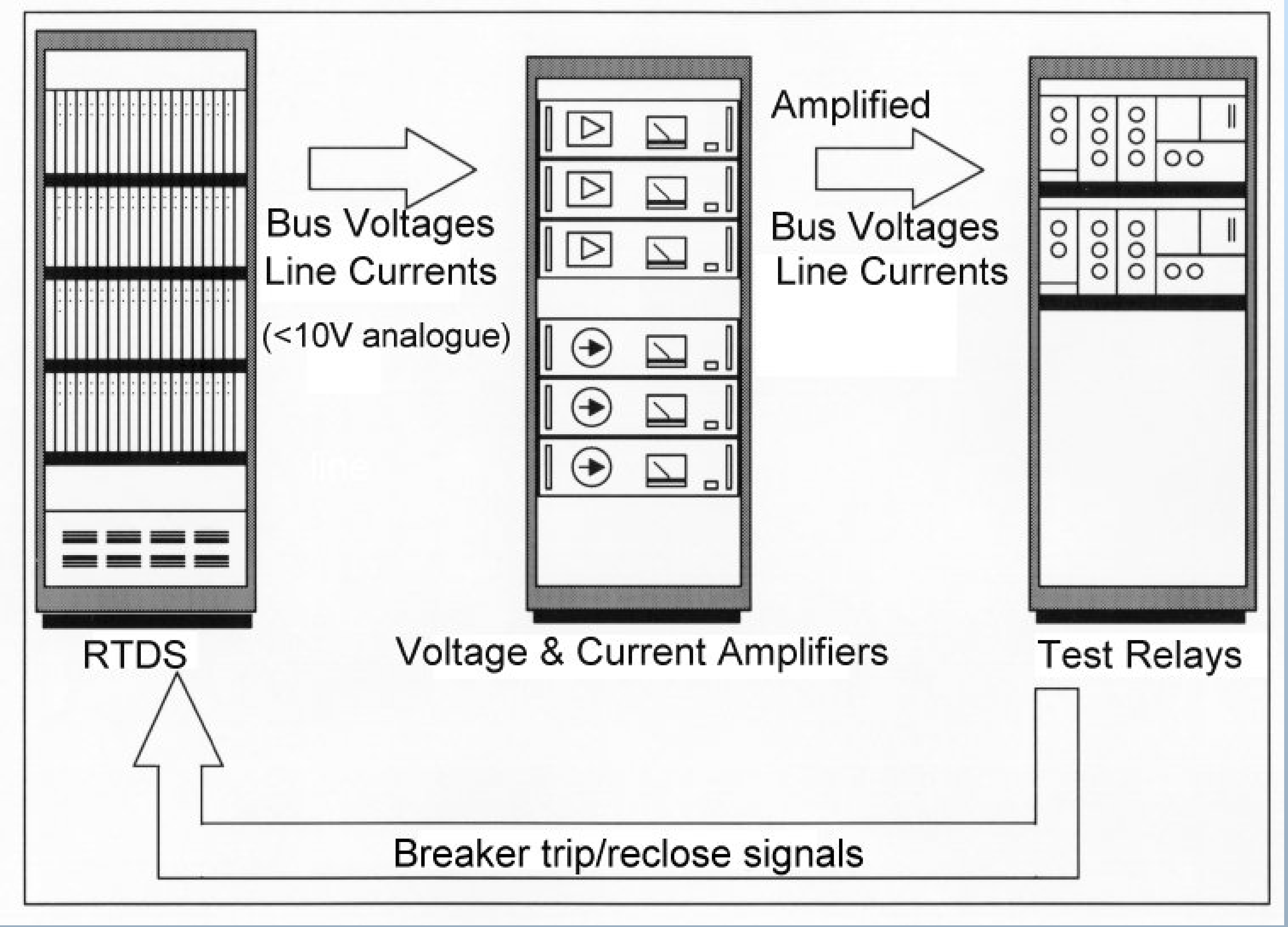
  12 cylinders, 7.92 MW, 514rpm
- Four Westinghouse Generators

  7.2 MW, 6.6kV, 60 Hz, 0.7 PF
- Two Alstom Propulsion Motors

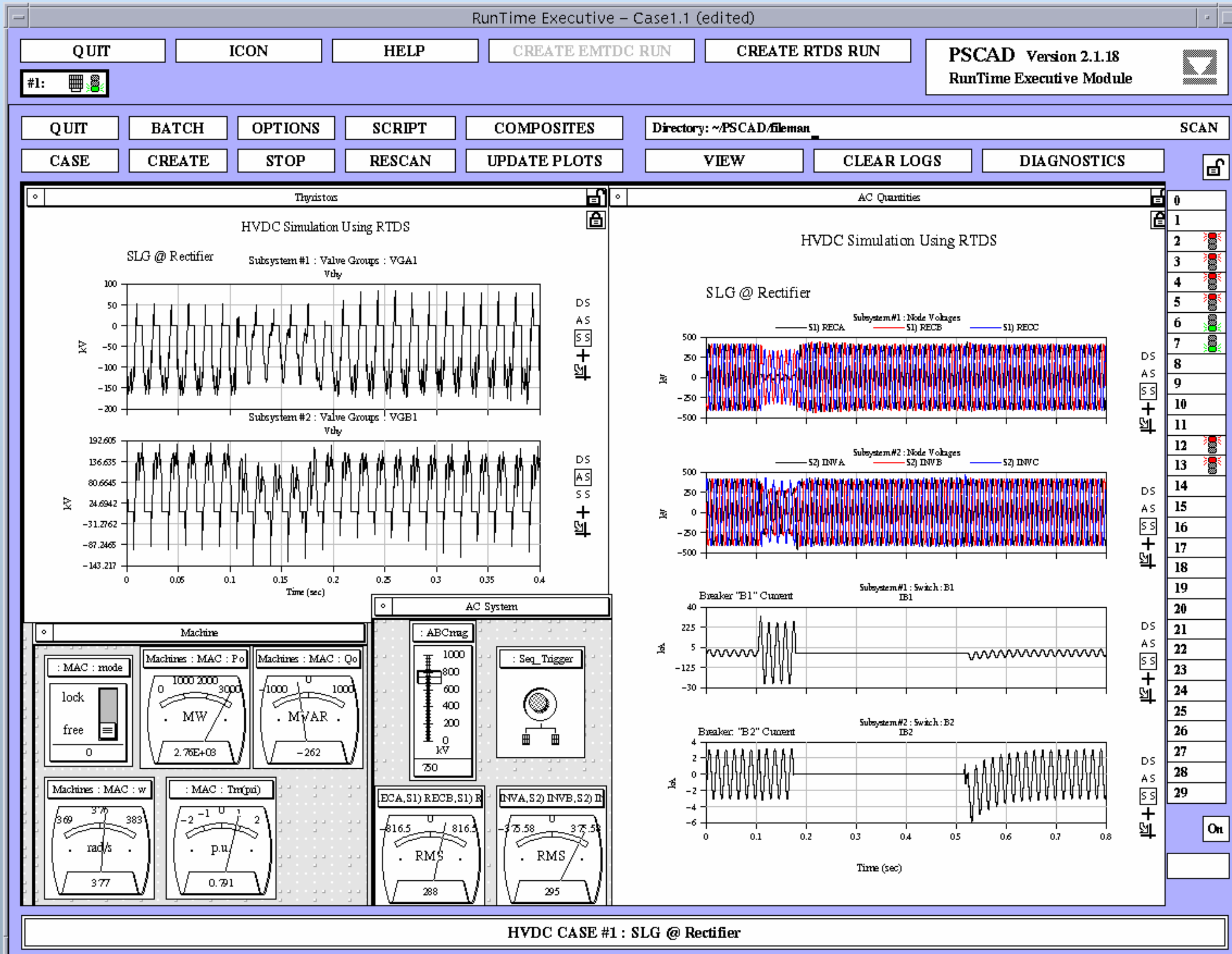
  15,000 HP, 2,320 V, 160 rpm

  Variable frequency cyclo-converter drive – 0 to 13.3Hz

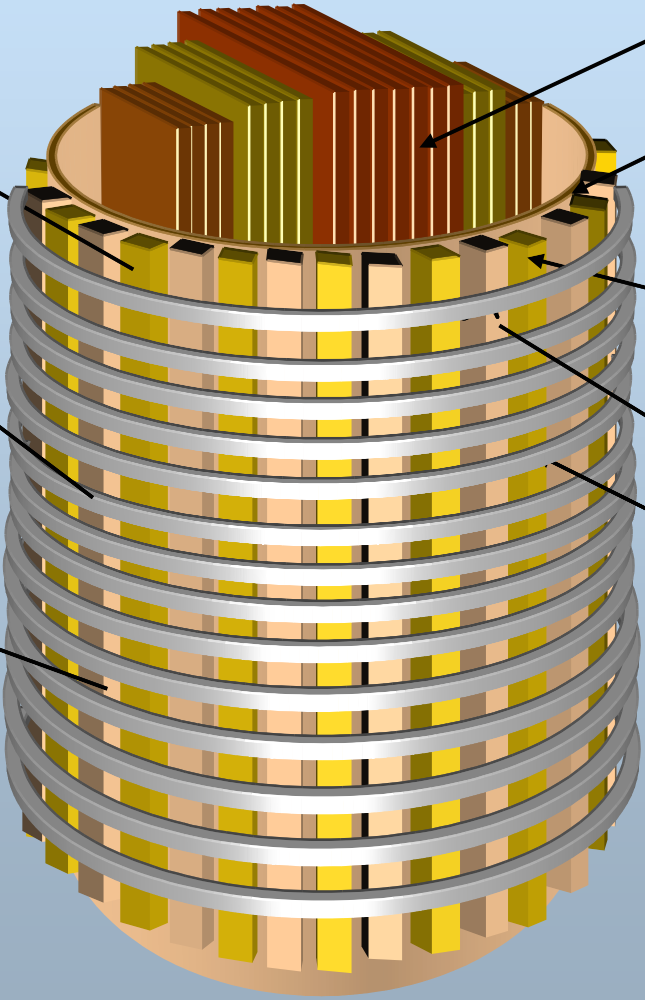
Application of Real Time Digital Simulator



RTDS: Ability to test hardware and controls under real-time conditions

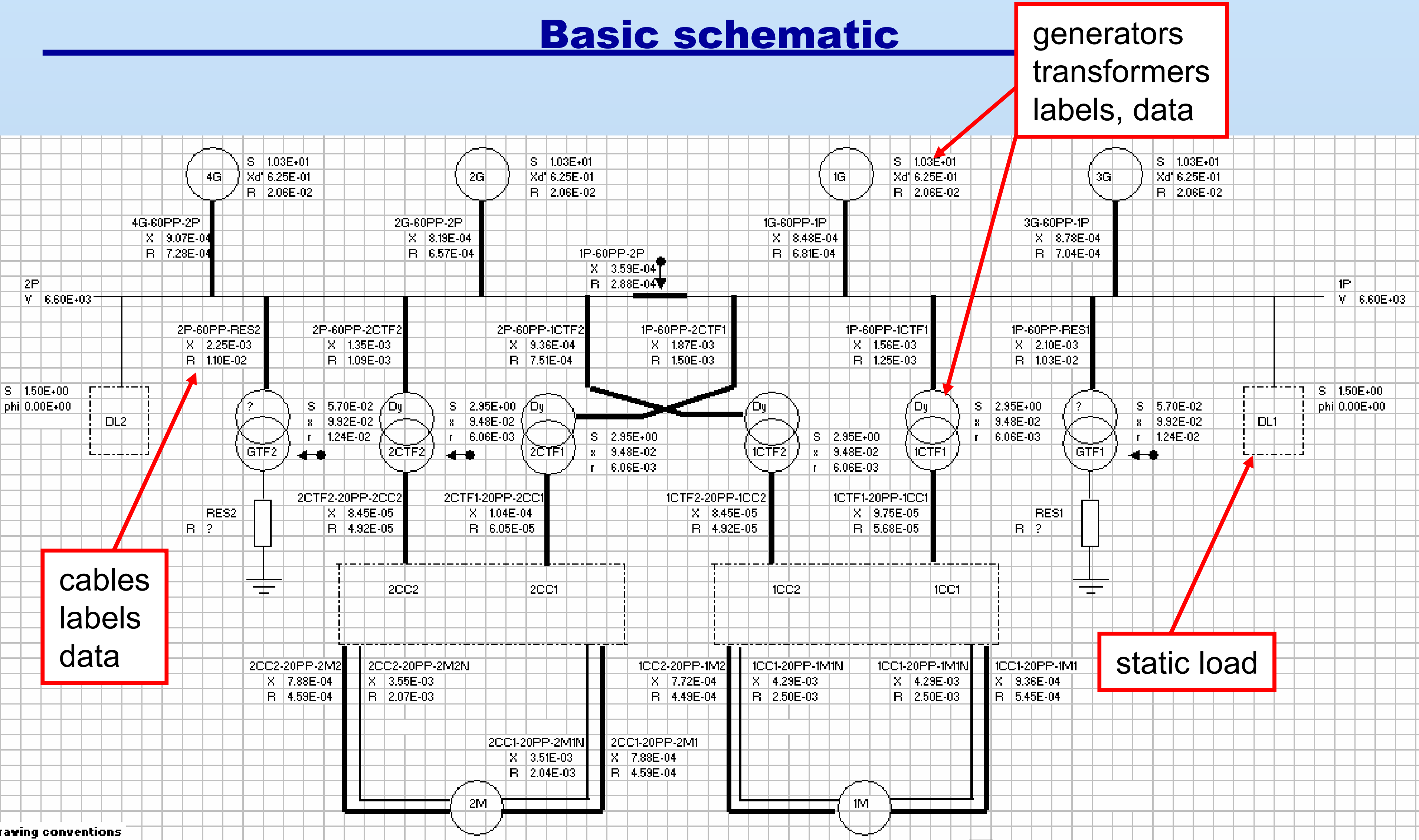


Other CAPS Programs: HTS Transformer



Representative only
Not to scale

Basic schematic



3ph generator terminal fault – fault currents and bus voltage

Table 5.2.1a I(sym) and I(asym) on 6.6kV Bus with Contribution from HV Loads Only

	EDSA Analysis		% difference between EDSA and DDS		DDS 300-2		% difference between ETAP and DDS		ETAP Analysis		% difference between EDSA and ETAP	
Item	I(sym)	I(asym)	I(sym)	I(asym)	I(sym)	I(asym)	I(sym)	I(asym)	I(sym)	I(asym)	I(sym)	I(asym)
Gen 1 swbd	24,500	39,098	-4.45%	-4.03%	25,640	40,740	-4.05%	-3.00%	24,602	39,517	-0.41%	-1.06%
Gen 2 swbd	24,492	39,066	-4.28%	-3.64%	25,588	40,542	-3.89%	-2.60%	24,593	39,486	-0.41%	-1.06%
Gen 3 swbd	24,475	39,001	-4.48%	-4.11%	25,623	40,674	-4.09%	-3.07%	24,576	39,424	-0.41%	-1.07%
Gen 4 swbd	24,483	39,033	-4.39%	-3.88%	25,606	40,608	-3.99%	-2.84%	24,585	39,455	-0.41%	-1.07%
1PHV SWBD (stbd)	24,573	39,368	-4.68%	-4.62%	25,780	41,276	-4.31%	-3.68%	24,670	39,768	-0.39%	-1.01%
2PHV SWBD (port)	24,573	39,368	-4.68%	-4.62%	25,780	41,276	-4.31%	-3.68%	24,670	39,768	-0.39%	-1.01%
Bow Thruster SWBD	23,298	34,774	-4.01%	-3.29%	24,272	35,957	-3.72%	-2.71%	23,368	34,983	-0.30%	-0.60%
SSMG swbd (stbd)	23,022	27,901	-4.43%	-3.89%	24,088	29,030	-3.96%	-2.81%	23,133	28,213	-0.48%	-1.11%
SSMG swbd (port)	23,238	28,829	-4.46%	-3.94%	24,324	30,012	-3.88%	-2.36%	23,381	29,306	-0.61%	-1.63%
SSTF traf (stbd)	23,694	36,139	-4.56%	-4.38%	24,825	37,794	-4.15%	-3.36%	23,795	36,525	-0.42%	-1.06%
SSTF traf (port)	23,754	36,531	-4.57%	-3.92%	24,892	38,023	-4.02%	-3.17%	23,892	36,816	-0.58%	-0.77%

Note:

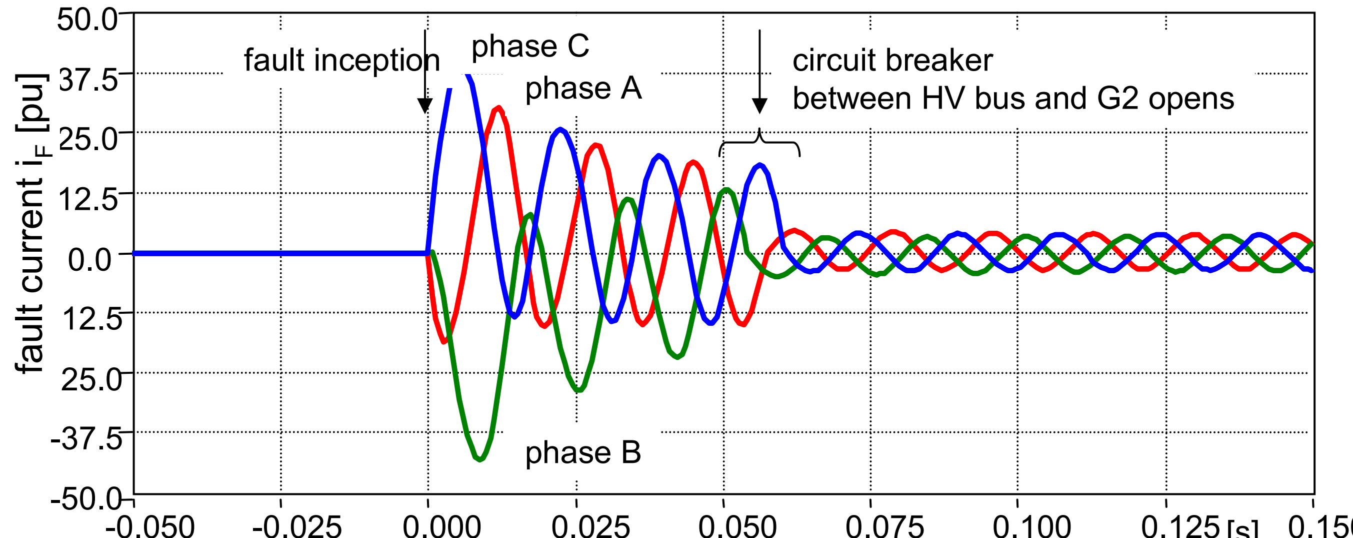
1. See note 1 of sheet 10 of Avondale DWG 61-01-03.
2. Contains contributions from the four SS Generators, an MG set, the bow thruster and the (M) 450V lumped load via 2SSTF.
3. Gen Xd'' = 15.5% & X/R=30.3, 2SSTF Xd''=6.9% & X/R=7.55

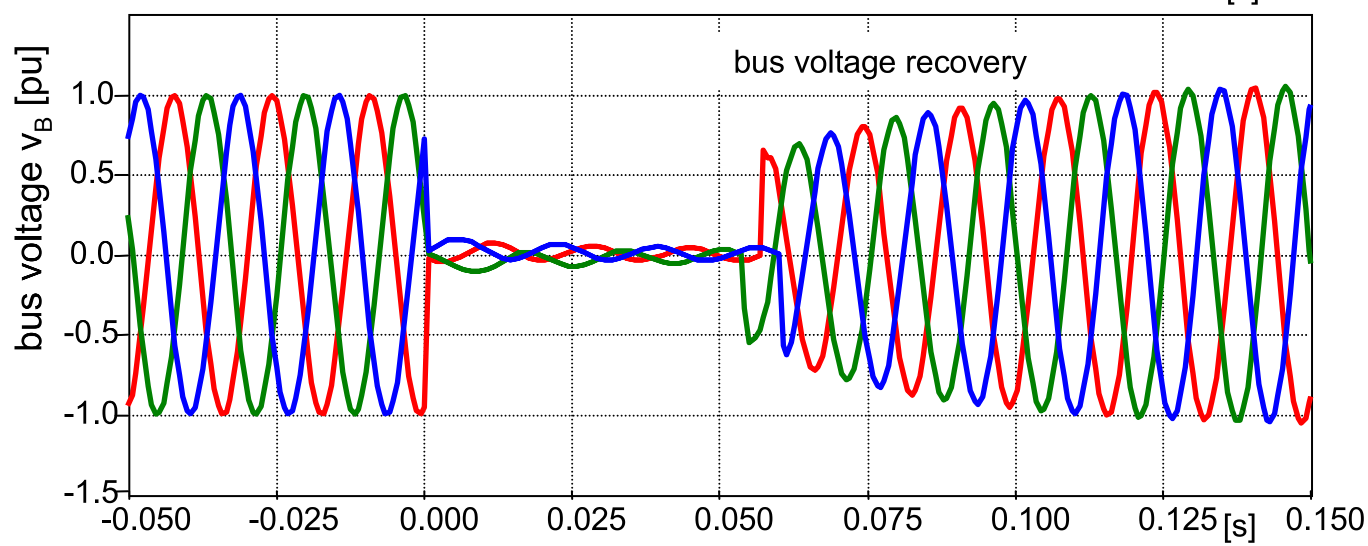
Table 5.2.1b I(sym) and I(asym) on 6.6kV Bus with Contribution from HV Loads Only

	EDSA Analysis		% difference between EDSA and DDS		DDS 300-2		% difference between ETAP and DDS		ETAP Analysis		% difference between EDSA and ETAP	
Item	I(sym)	I(asym)	I(sym)	I(asym)	I(sym)	I(asym)	I(sym)	I(asym)	I(sym)	I(asym)	I(sym)	I(asym)
Gen 1 swbd	24,757	39,409	-3.44%	-3.27%	25,640	40,740	-4.26%	-3.20%	24,549	39,438	0.85%	-0.07%
Gen 2 swbd	24,748	39,376	-3.28%	-2.88%	25,588	40,542	-4.09%	-2.80%	24,541	39,407	0.84%	-0.08%
Gen 3 swbd	24,731	39,310	-3.48%	-3.36%	25,623	40,674	-4.29%	-3.26%	24,524	39,346	0.84%	-0.09%
Gen 4 swbd	24,739	39,343	-3.39%	-3.12%	25,606	40,608	-4.19%	-3.08%	24,532	39,377	0.84%	-0.09%
1PHV SWBD (stbd)	24,832	39,686	-3.68%	-3.86%	25,780	41,276	-4.51%	-3.84%	24,617	39,689	0.87%	-0.01%
2PHV SWBD (port)	24,832	39,686	-3.68%	-3.86%	25,780	41,276	-4.51%	-3.84%	24,617	39,689	0.87%	-0.01%
Bow Thruster SWBD	23,418	34,679	-3.52%	-3.56%	24,272	35,957	-4.26%	-3.37%	23,239	34,744	0.77%	-0.19%
SSMG swbd (stbd)	23,240	28,076	-3.52%	-3.29%	24,088	29,030	-4.15%	-2.96%	23,089	28,172	0.65%	-0.34%
SSMG swbd (port)	23,462	29,012	-3.54%	-3.33%	24,324	30,012	-4.20%	-3.00%	23,303	29,111	0.68%	-0.34%
SSTF traf (stbd)	23,934	36,407	-3.59%	-3.67%	24,825	37,794	-4.36%	-3.53%	23,746	36,458	0.79%	-0.14%
SSTF traf (port)	23,996	36,622	-3.60%	-3.68%	24,892	38,023	-4.36%	-3.56%	23,806	36,671	0.80%	-0.13%

Note:

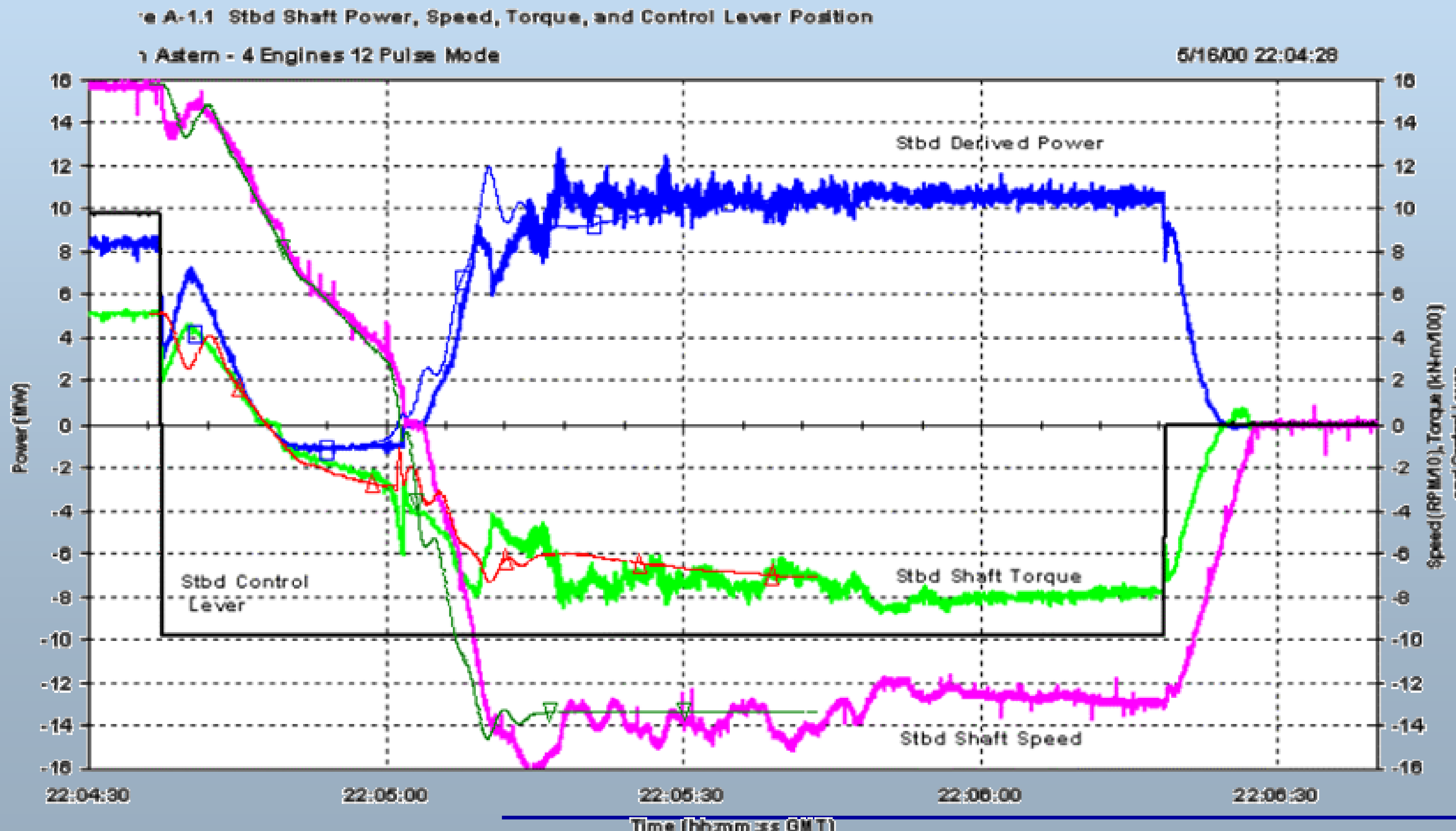
1. See note 1 of sheet 10 of Avondale DWG 61-01-03.
2. Contains contributions from (M2) HV lumped load, the four SS Generators and (M) 450V lumped load
3. The (M) 450V lumped load impedance was converted to a 6600V base and the load applied directly to the HV switchboard
4. The MG set and bow thruster were combined into a lumped load and applied directly to the HV switchboard
5. The buses for the MG sets, the bow thruster and the service tranformers were treated as no-load/non-contributing buses
6. The service tranformer 2SSTF and its secondary conductor impedances were neglected
7. Gen Xd'' = 15.5% & X/R=30.3, 2SSTF Xd''=6.9% & X/R=7.55



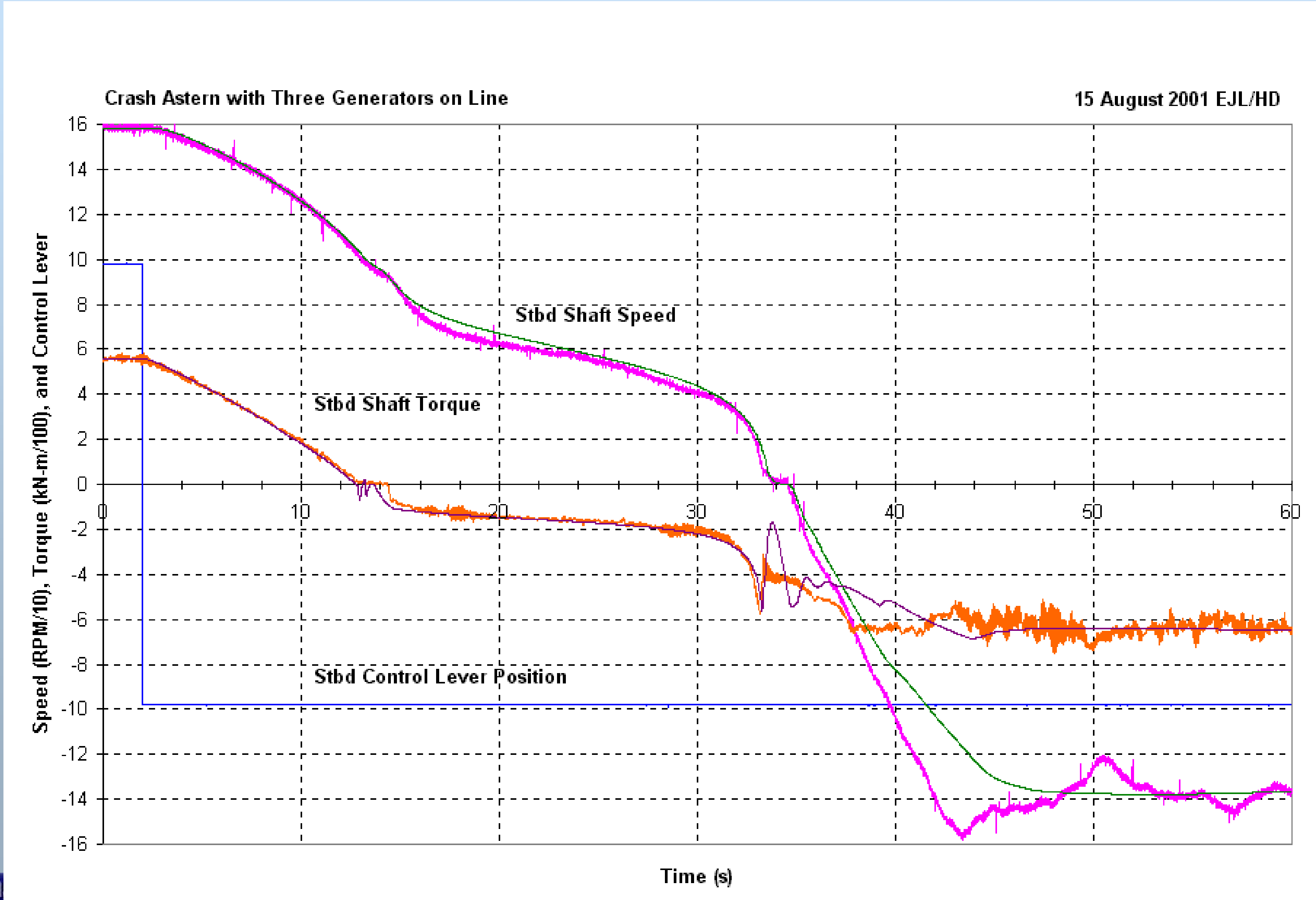


Crash Astern (EMTDC)

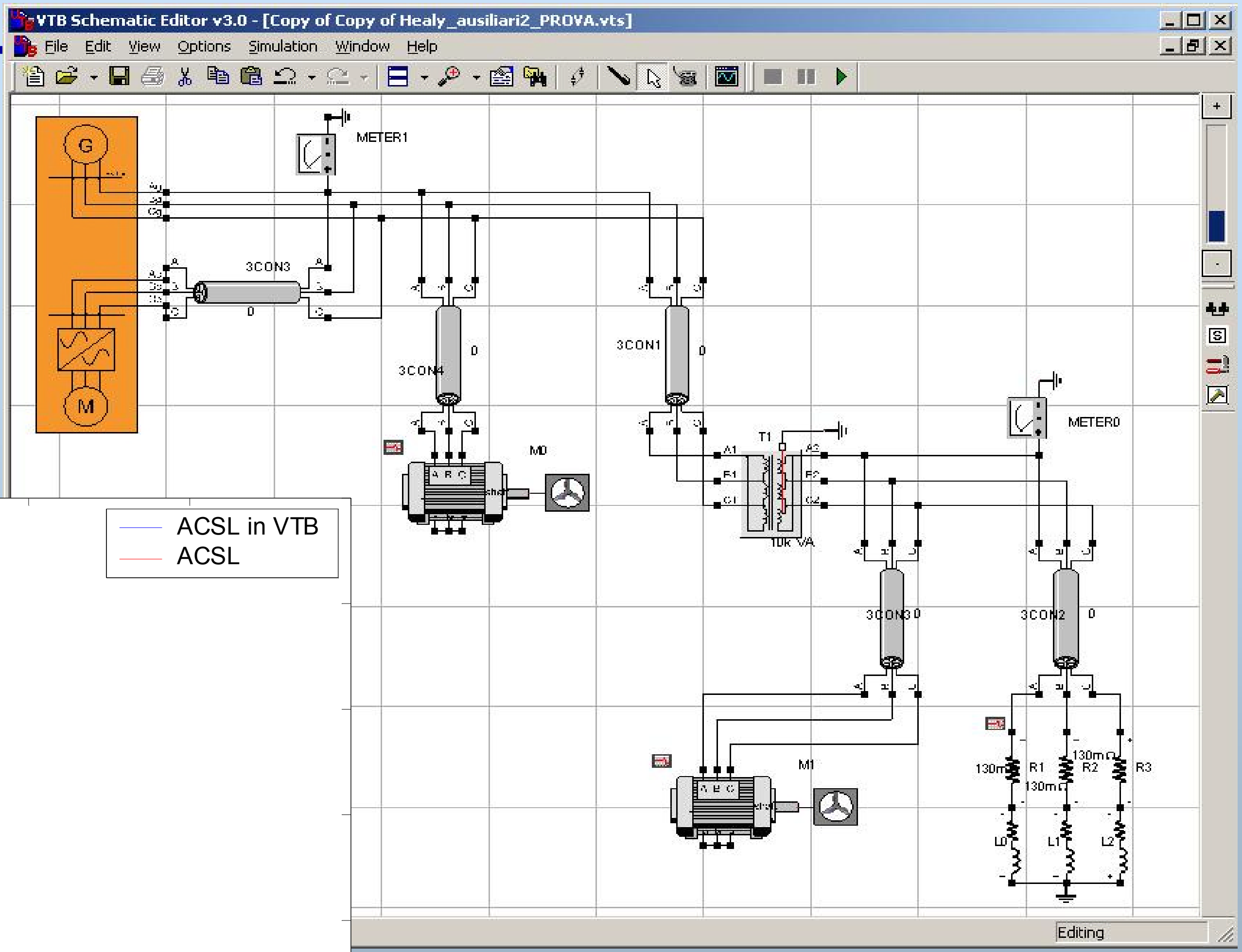
Speed Control

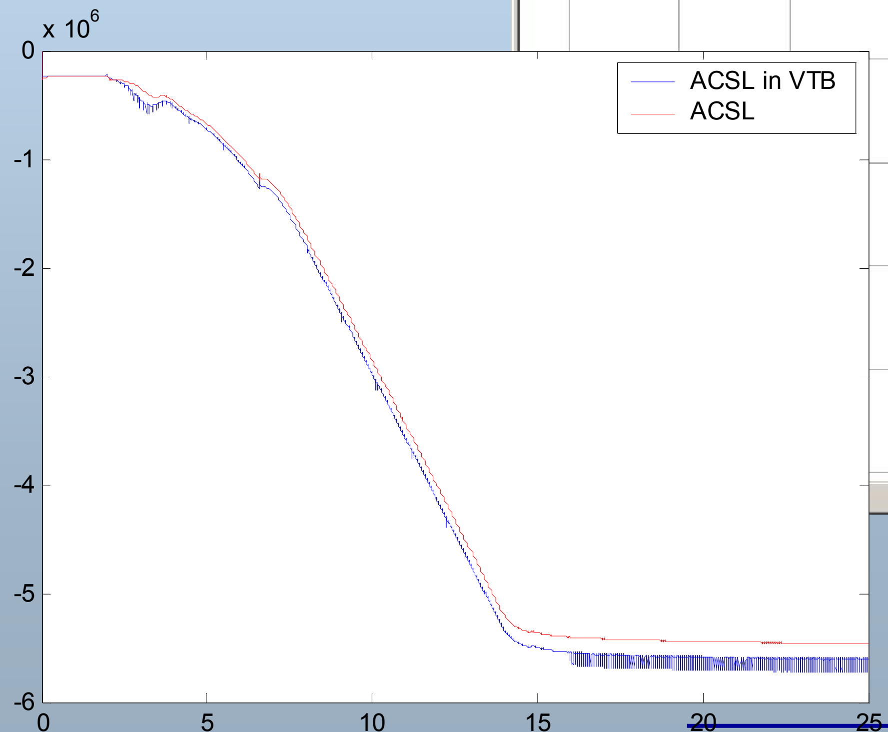


ACSL – Crash Astern

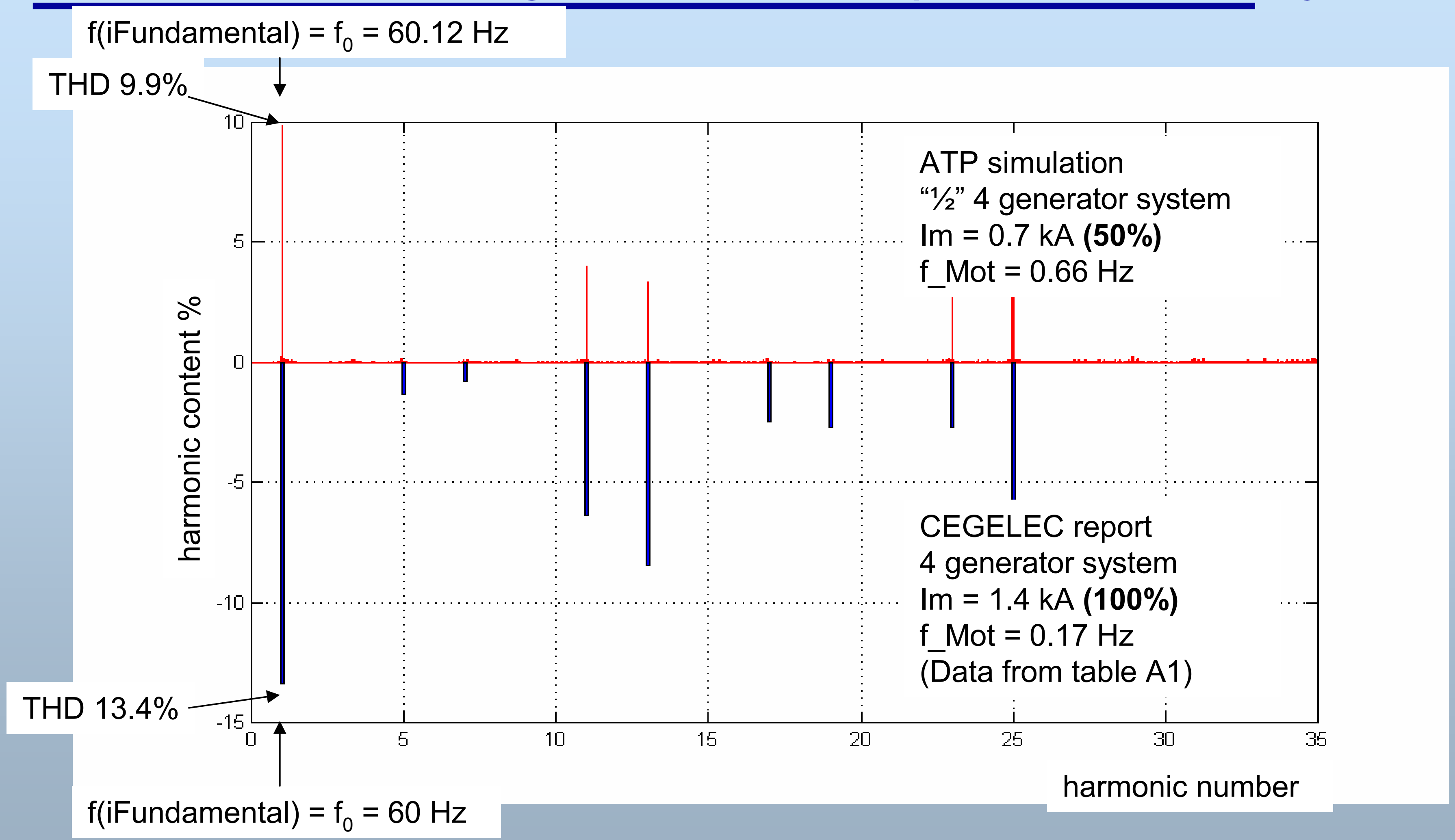


VTB: Co-simulation





Voltage Harmonics 8 RPM – Comparison with CEGELEC analysis



Integrated Power Management
First Year Tasks

- Model electrical system architecture of small aircraft (e.g., Gulfstream jet) on the real-time digital simulator
  - representation of the power system
    - electrical system
    - converters and drives
    - control systems (for energy management)
      - load sharing
    - mechanical aspects
      - speed-torque time relationships
    - new technologies
      - fuel cells
  - level of modeling
    - averaged models
    - switching models
  - develop test cases for simulation and verification
- set up evaluation criteria and procedures for continuation work
  - analysis set-up for year two
    - electrical
      - load flow and harmonics
      - large-scale transients
    - electro-mechanical transients

Build on prior experience

The AMSC-Reliance Electric Phase I development of a 200 HP motor successfully concluded in 1996

The AMSC-Rockwell 1,000 HP motor (Phase II) satisfactorily tested in Summer 2000 and has since exceeded performance expectations

Siemens Large Drive Division in cooperation with Siemens R&D center at Erlangen recently tested a 380 kW HTS-motor, funded by the German Ministry for Education and Research (BMBF).

** Courtesy of American Superconductor*

Present development at ASC

- 5000 hp, 1800 rpm, 60 Hz synchronous motor
- Line voltage 6.6 kV
- HTS field winding BSCCO-2223 operating at
  -405°F cooled by Gifford-McMahon cryogenic refrigerators
- Stator winding cooled with fresh water
- Frame dimensions 44 inch x 62.75 inch
- Weight – 15,000 lbf
- Efficiency – 97.7%
- Designed for Disassembly

* *Courtesy of American Superconductor*

Superconducting Motors
First Year Tasks

- Gather relevant design data
  - HTS materials
  - Cryocoolers
  - Insulators
- Survey prior and existing development programs
  - Map different types of rotating machinery
  - Determine best approach for this program
- Establish power rating targets for aircraft-relevant motors
  - Assess potential gains in performance (weight, size, etc.)
  - Reconcile with program needs (system integration)
- Establish development path for demonstration and implementation of a superconducting motor