



Reinventing Power Programs Through Sustainability Focused Curriculum: An Update

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Mission Capable, Persistent and Survivable

Naval Platforms

Office of Naval Research

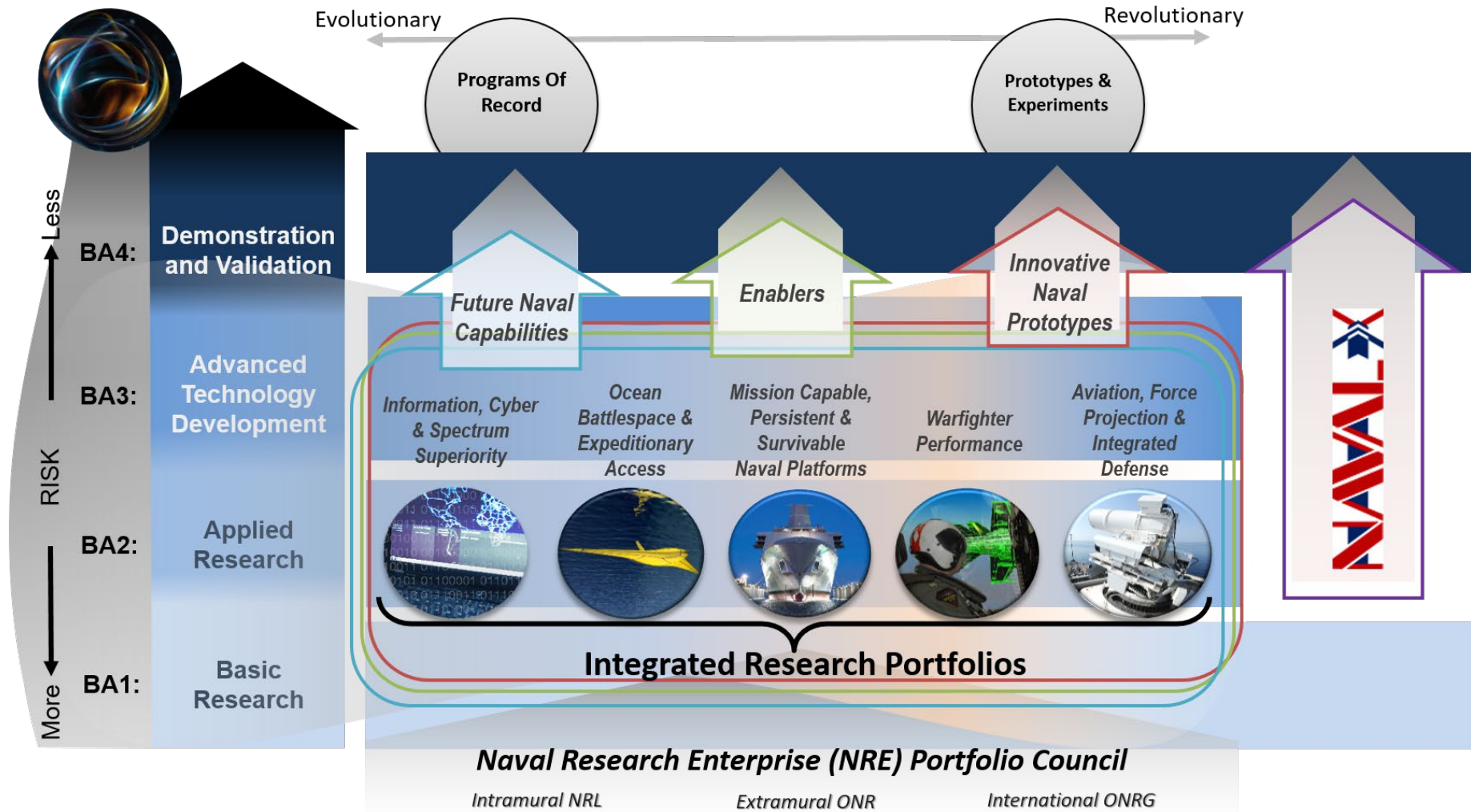
National Science Foundation

21/22 October 2022

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The Portfolio – ONR Departments





NAVAL PLATFORMS

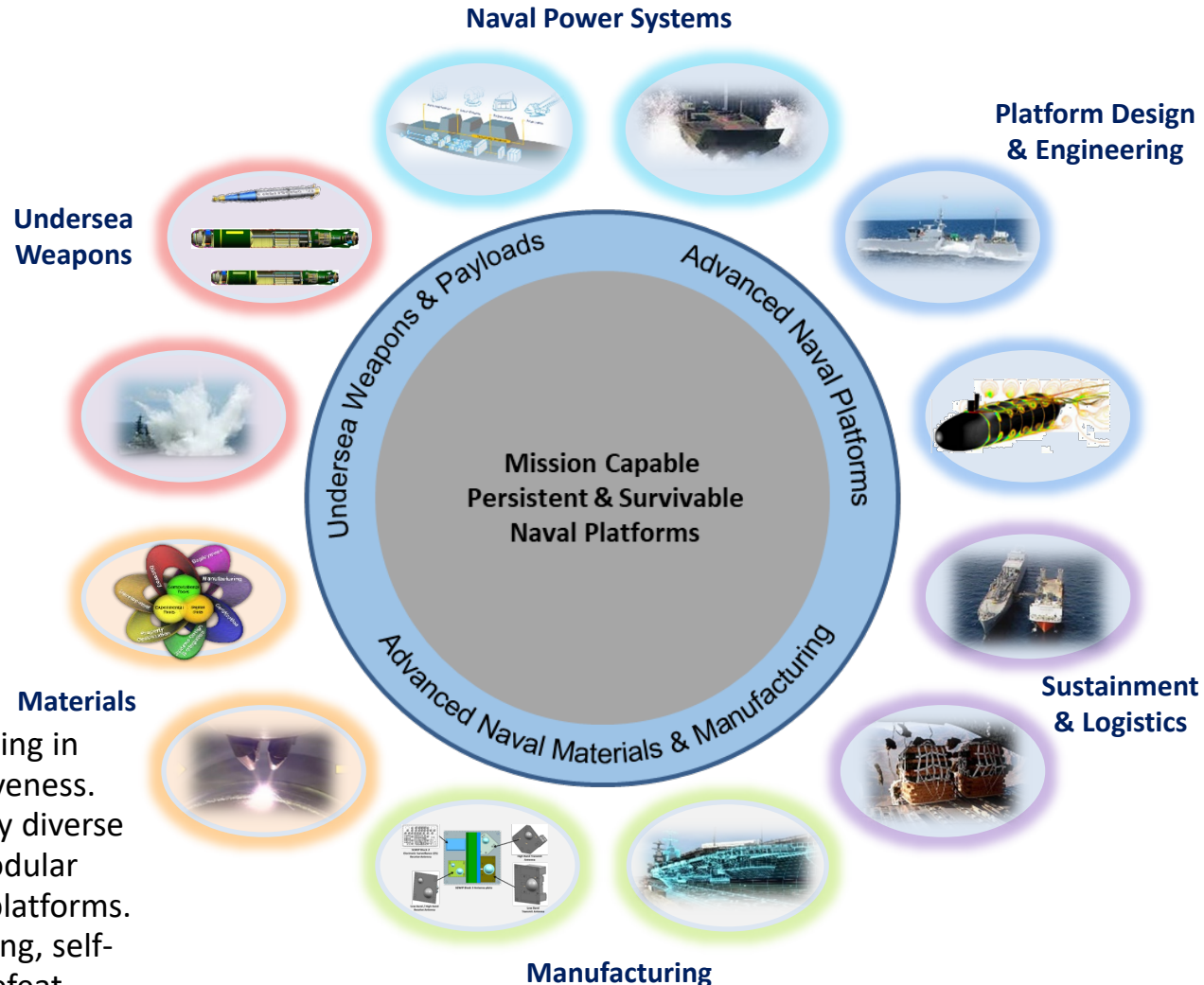
Mission Capable, Persistent, and Survivable

AT A GLANCE

Research on concepts, systems and component technologies that improve the performance and survivability of Navy and Marine Corps platforms in an increasingly distributed yet interconnected force.

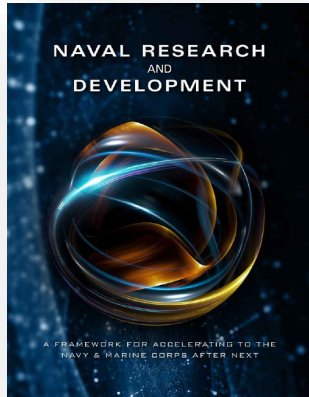
WHY IS THIS IMPORTANT

- Threats to the fleet/force are increasing in number, range, precision and effectiveness.
- Sustainable operations in increasingly diverse environments require affordable, modular survivable and rapidly upgradeable platforms.
- Maritime superiority requires enduring, self-sustaining platforms able to deter/defeat aggression through overwhelming capability.





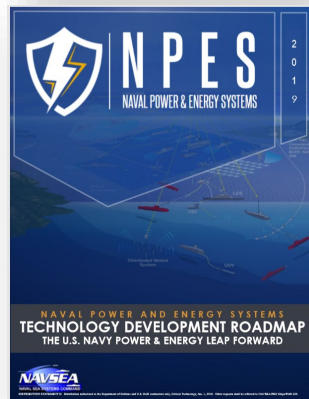
Strategic P&E Guidance



From Naval R&D Framework

- Operational Endurance Priority:

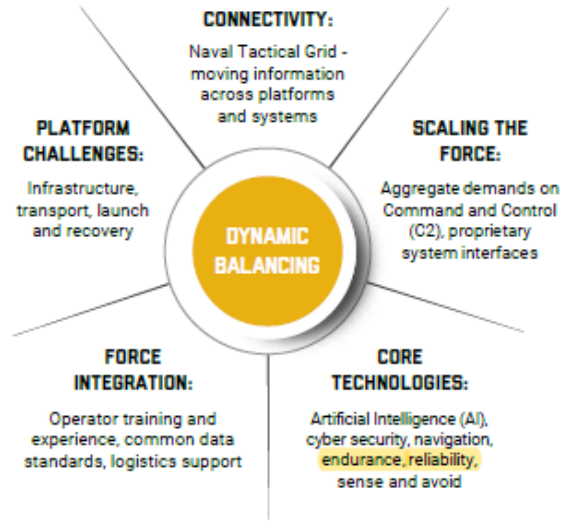
- Enable maneuverability, efficiency and resiliency for sustained operations by warfighters, systems and platforms (regardless of the threat or operating environment)
- Improve platform-level energy storage/efficiency for propulsion and weapons systems



The 2019 Naval Power & Energy Systems Technology Development Roadmap (NPES TDR)

- Reinforces power and energy as the foundation of the kill chain.
- Promotes energy harvesting and improved efficiency in components, power systems, and energy conversion systems

Strategic P&E Guidance



“New and converging technologies will have profound impacts on the security environment. Artificial intelligence, autonomy, additive manufacturing, quantum computing, and new communications and energy technologies could each, individually, generate enormous disruptive change.”



S&T Objectives: Develop Courses and Laboratories for Electric Energy Education

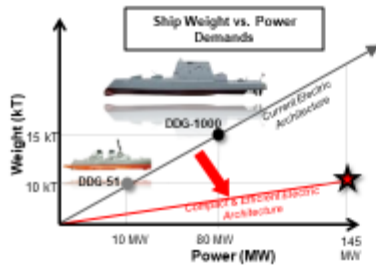
- A better-trained supply of U.S. graduates in STEM to tackle various research challenges in the Navy
- Adding flexibility and safety to ensure that they will be useable in a variety of future Navy courses and learning needs
 - Do so by enabling all universities to provide a first-rate education and educate students in large numbers



Motivation: High Power and Pulsed Power Applications



Motivation



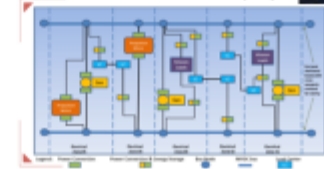
- Future Power Payloads:**
- Future Radar
 - Rail Gun
 - Hybrid propulsion
 - Solid State Laser
 - Future EW systems
 - Future Illuminator
 - Hull Sensor
 - Vertical Launch System
 - Laser Weapon System
 - Multi-Function Towed Array
 - Etc.



Compact power systems are required to enable future payloads → Wide bandgap semiconductors:

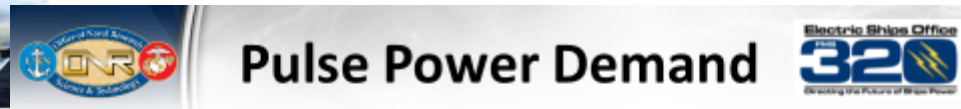
- GaN has a 10X higher Baliga Figure of Merit than SiC
- Vertical device architecture is enabled by large area, high quality, truly bulk substrates now available
- Significant materials challenges to realize high performance devices
 - Selective-area, controlled p-type doping
 - Low background doping for drift layers

INTEGRATED POWER & ENERGY SYSTEMS (IPES)



- It:
- Evolutionary
 - Shared energy
 - Advanced to systems level
 - Affordable, 50
 - Zero 12kV energy
 - MVDC IPES
 - April 2016-18

20kV switches needed for 12kV DC Power

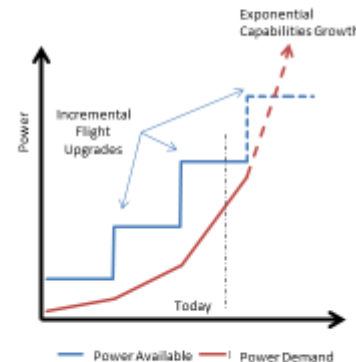


Pulse Power Demand



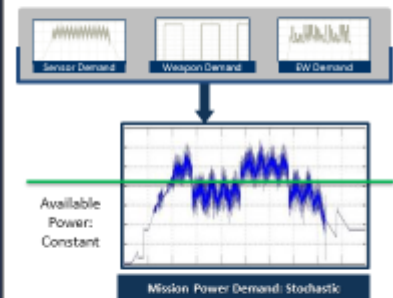
MORE POWER

STEP CHANGE INCREMENTAL DEVELOPMENT OF POWER GENERATION VS. INCREASE IN POWER REQUIREMENT OVER TIME



DIFFERENT DEMAND

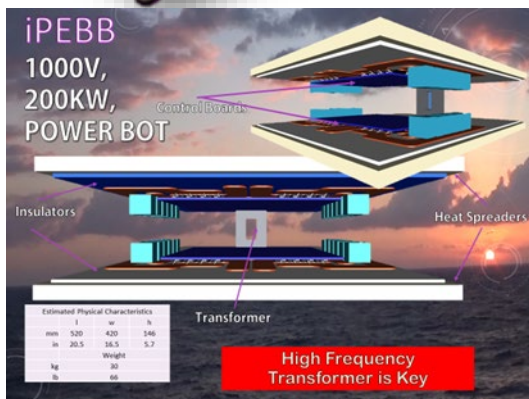
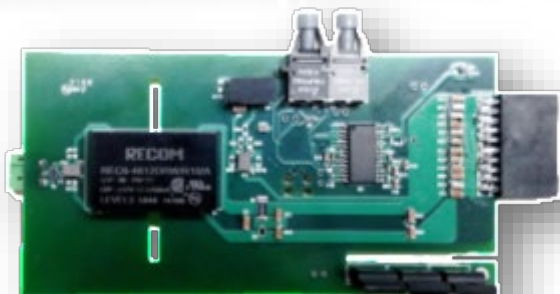
NEW CAPABILITIES DEMAND PULSE AND STOCHASTIC POWER



CURRENT AVAILABLE POWER ABOARD SHIPS CANNOT SUPPORT DYNAMIC LOADS

Increased Warfighting Capability to Overmatch the Threat Demands Power

Technical Advances



- Silicon Carbide Power Switches
- 100kHz or greater switching
- FPGA
 - Field Programmable Gate Arrays
 - High Speed Control
 - Intelligent Power Modules
- High Frequency Magnetics
- Highly Integrated PEBB (Navy iPEBB) Based Converters
- Enables Power Electronic Power Distribution System Concept

Curriculum Completed and on CUSP in WBG Theory and Application through an ONR Grant

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Navy Power Electronic Building Blocks & Power Electronics Power Distribution System

Development of SiC-Based PEBB 1000 (2014-2017)

R. Burgos, D. Boroyevich, J. Wang, and I. Cvetkovic
This work was supported by ONR Grant N00014-16-1-2956

- Designed for operation under the harsh dV/dt environment. EMI containment strategy implemented in the gate drivers, power supplies, and digital control
- Features high-bandwidth current sensors integrated in the gate driver for extremely fast protection and peak-current mode control
- Designed for the switching cycle control that enables dc-link capacitor voltage balancing within one switching cycle

SiC Module 1.7 kV, 300 A

Gate-Driver with a High-Bandwidth Current Sensor

Range > 800 A
Error < 1%
BW > 1 MHz
di/dt > 50 A/ns

1000 V nominal DC voltage
100 A nominal current
100 kHz switching freq.
Efficiency 98%
Weight 26 lb

Fault Current cleared in 1 μs!

Thermal interface, Power terminals, Control interface, HMI

PEPDS is an Integrated Power and Energy Power Distribution System Challenge

- Integrated Power, Propulsion, Protection, Filtering, Storage, and Control
- Distribution Converters provide protection, filtering, and (with Energy Magazines) storage
- Distribution Converters create an interface for every load
 - No single interface standard for all loads.
 - AC or DC, Frequency, Voltage, Power, etc. are tailored to meet individual load requirements.
- Common Interface Solutions for All Loads – high commonality
- Integrated Electrical, Thermal, and Mechanical Control

Least Replaceable Unit, Most Common Denominator
-- Key To Enabling PEPDS

Development of the PEBB 6000 Using Gen3 10 kV, 240 A SiC MOSFET Modules in Full-Bridge Configuration

R. Burgos, D. Boroyevich, I. Cvetkovic, and D. Dong
This work was supported by ONR Grant N00014-16-1-2956

PEBB 6000 LRU

Using Wolfspeed XHV-6 10 kV 240 A SiC MOSFET modules

Half-bridge converters

Full-bridge structure
Full-Bridge PEBB 6000
Power density = 23.3 kW/l

Objectives

- Electrothermal design optimization of PEBB 6000 rated at 6 kV, dc, 1 MW, 240 A, targeting 10 MW/m³, η = 99 %, and PDIV = 30 kV
- Targets Achieved:
 - Partial discharge inception voltage (PDIV) of 30 kV
 - Power density of 16 MW/m³, η = 99.4 % (full-bridge) network including wireless power transfer and d power supplies

Navy Integrated Power Electronics Building Block (Navy iPEBB) (2019-2023)

C. DiMarino, R. Burgos, D. Boroyevich, I. Cvetkovic, R. Raju (Fast Watt, LLC)
This work was supported by ONR Grant N00014-16-1-2956

- Objective:** To design a high-density, integrated PEBB with galvanic isolation and high manufacturability.
- Tasks:**
 - Employ multi-physics finite element analysis to design high-density, efficient, and reliable Navy iPEBB
 - Evaluate state-of-the-art substrate materials
 - Prototype and test H-bridge with 1.7 kV SiC MOSFETs
 - Prototype and test 500 kHz, 250 kW transformer with 20 kV isolation

Navy iPEBB Target Specifications

Parameter	Target Value
Voltage	1 kV dc
Power	250 kW
Switching Frequency	500 kHz
Power Density	12 kW/l
Weight	35 lbs
Isolation Voltage	20 kV

Fig. 1: High-efficiency, bidirectional DC/DC, DC/AC iPEB

Fig. 2: Rendering of the iPEBB, multi-layer substrate prototype, and current dimensions and weight

Navy Integrated Power and Energy Corridor (NiPEC)

This work was supported by ONR Grant N00014-16-1-2956

Power and Energy Corridor (iPEC)

Example Power Corridor

Integrates a single modular array of all the components of the electrical distribution system:

- Manufacturing
- Protection
- Isolation
- Control
- Energy Storage for the main bus power throughput

Single Bulkhead Sample: Side View

Developing algorithm
Cable allocation algorithm
Thermal simulations of multiple cables, terminals and connections
Use, size and location of energy storage



Background : Magnetics in Power Conversion

Magnetics - key factor determining the size, weight and efficiency of power converters

Multiple functions -

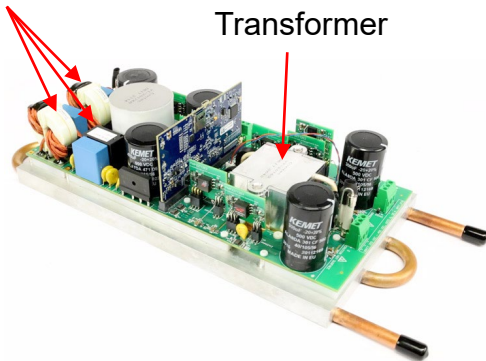
Transformers: voltage and current scaling, sensing

Inductors: energy storage, circuit resonance, filtering, current limiting

Varied requirements -

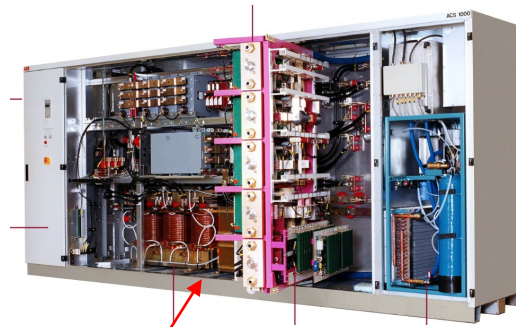
high permeability for line-frequency transformers, distributed gaps or low permeability for inductors, high impedance and damping at noise frequencies for CM chokes, + low magnetostriction/audible noise, low loss, high saturation flux, etc.

Common/ differential mode filters



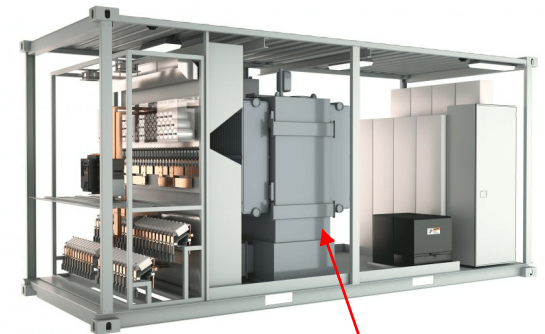
On-board EV charger
(TI reference design, ti.com)

Transformer



Output filter

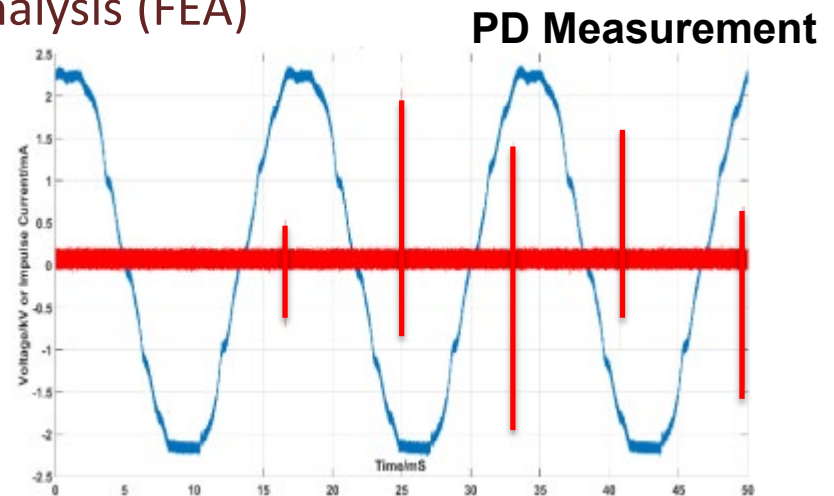
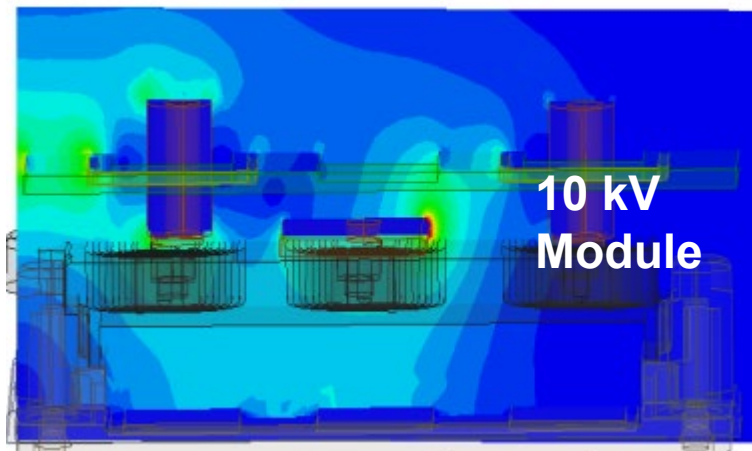
Medium Voltage Motor Drive
(ABB ACS1000, abb.com)



Step-up transformer
Utility Solar Inverter
(GE Power Conversion, ge.com)

Key Challenges

- Heightened EMI emissions due to high switching frequency, fast dv/dt , and large parasitic capacitances to ground
 - Mitigation: use impedance-based EMI channeling technique
- Design of high-voltage insulation strategy capable of withstanding high electric fields under fast PWM conditions
 - Mitigation: proper selection of materials, partial discharge (PD) measurements, finite element analysis (FEA)



Curriculum Development completed in Sustainable Education in EMI, Common Mode Differential Mode theoretically speaking and in practice, through an ONR Grant, N000141812601, Dr. Andy Lemmon, University of Alabama, and a second in Creepage and Clearance standards development, ONR Grants N000141812547, Dr. Rob Cuzner, University of Wisconsin, Milwaukee; N000141812623, Dr. Lukas Graber, Georgia Tech, and N000141612956, Dr. Michael Steurer, Florida State University. In the near future, sustainable education in machine and drive insulation



ONR Grants

1. Center for Reforming Undergraduate Education in Electrical Engineering Energy Systems – A Critical Infrastructure for National Security Jun1, 2006 – Sept 30, 2012, \$1,292,441 + \$38,062
2. Center for Developing and Disseminating a Graduate/Undergraduate Curriculum 6/1/2011- 02/29/2016, \$828,051 + \$56,362
3. Increasing Electric Power and Energy Engineering Pipeline Nationwide 3/15/2014- 4/30/2016, \$106,000
4. Offering of Web-Enabled, Instructor-Taught Online Courses based on ONR-Funded Graduate Power Curriculum 6/2015 – 05/31/2020, \$590,000
5. National Dissemination of the CUSP™ Electric Power Curriculum 8/10/2018- 5/31/2021, UMN Share from TTU \$21,392
6. Developing WBG-Based, Extremely Low- Cost Laboratories for Power Electronics, Motor Drives, and Power System Protection and Relays for National Dissemination 01/01/2019 – 12/31/2023, \$701,747
7. A Low-Cost Scalable Tabletop Emulator for Shipboard Power System 07/01/2022- 12/31/2026, \$788,192



The Most Important Resource: People

Objective / Goal

- Revive and Enhance Education - Prepare next generation of Navy electrical & power engineers
- Meet increasing demands in power-related fields in the Navy and elsewhere
- Educate naval officers to maintain, operate, & sustain naval power systems

Summary of Effort

- Develop 19 courses in Electric Power & Energy Systems
- Disseminate widely by offering course materials free online to all U.S. universities for classroom and distance learning

Major Participants

- Ned Mohan – University of Minnesota
- Consortium of Universities for Sustainable Power (CUSP) – 235 universities participating as of October 2022 (ref:<http://cusp.umn.edu/cusp-members.php>)



Recent Accomplishments

- 19 courses completed
- Adopted by USNA and Naval Postgraduate School for core and distance learning curriculum
- Over 450 faculty members are using the learning curriculum

Key Milestones / Projected Transition

- **Near:** Publication of all 19 courses complete; Additional courses Master's Program (TTU) commenced in FY19
- **Mid/Far:** Educate/Train Navy and Industry Power Engineering Workforce with emerging technologies



Questions?