Power Electronic Power Distribution Systems (PEPDS)

Executive Summary

A five-year program is proposed to develop the Power Electronic Power Distribution System (PEPDS). PEPDS is a new power, energy, and control distribution concept enabled by ONR-developed technology, including high-power-density high-efficiency power electronics, Silicon-Carbide (SiC) power semiconductors, and modeling and simulation design and analysis tools.

The goal of the PEPDS program is to achieve revolutionary changes to system design and operation by leveraging recent technology advances and developing both the applications to use them and the control and modeling capabilities needed to employ them, culminating in a megawatt-level test bed that will demonstrate the applicability to a Navy shipboard electrical system.

A 5-year development program is planned as shown in Fig. 1, which illustrates the 5 main areas of science and technology development needed:

- Navy integrated Power Electronics Building Block (iPEBB)
- Power Corridor
- Model is the Specification
- Control
- System Simulation

The Navy iPEBB is a modular universal converter building block that is a power-dense, self-contained, sailor-carryable unit. Multiple identical iPEBBs are combined to form any conversion requirements of the ship and are configured to the specific solution through software that is uploaded by the control system when the iPEBB is inserted into the system. The SiC-based technology provides dynamic behavior and switching that are significantly faster than current Si-based technologies.

The Power Corridor incorporates in a single modular entity all the components of the electrical distribution system for the main bus power throughout the ship: main bus cables, conversion, protection, isolation, control and energy storage. The PEBB-based corridor provides the encompassing structure that combines iPEBBs to create appropriate converters, developing the interfaces required for smooth plug-in of the iPEBB. Further, the corridor enables safe, resilient operations, simplifies logistics and training, supports distributed and point energy storage solutions, implements a reserved-space paradigm in the early stages of design, and reduces construction costs by enabling off-hull construction and testing and reducing cable routing challenges in place.

Model is the Specification is a concept that enables a standards-based design process for the Navy. Advances in digital real-time simulation create the opportunity to use the model itself as the specification for design and procurement of both hardware and software. In order to achieve this, there must be a 1-to-1 correspondence between the model of any component and its behavior in the shipboard system.

Unique control challenges exist at the iPEBB, the power corridor, and the ship-wide levels. The high-speed dynamic responsiveness of the new technology enables a precise ability to control the flow of power not

previously seen; this potential must be harnessed through new control capabilities. Control system methodologies along with methods for health monitoring and cyber security and capabilities for learning and adjustment to future requirements are addressed herein.

The system simulation challenge is to simulate ever larger systems with more models at multiple levels of fidelity. System simulations are required to examine the interplay between components, develop system architectures, and analyze ship-wide impacts. System simulations are also needed to evaluate the development progress. These simulations live far beyond the development and design stage; the models used in simulations become the specification for procurement; they become the software that tailors an iPEBB to a specific application; and they are an integral part of the control and monitoring system onboard the ship.

This document provides a detailed examination of the science and technology advances that build on recent ONR successes and that are required to achieve the PEPDS vision. This document also lays out a methodical five-year program for the integrated, cross-disciplinary, multi-variant development of those advances.

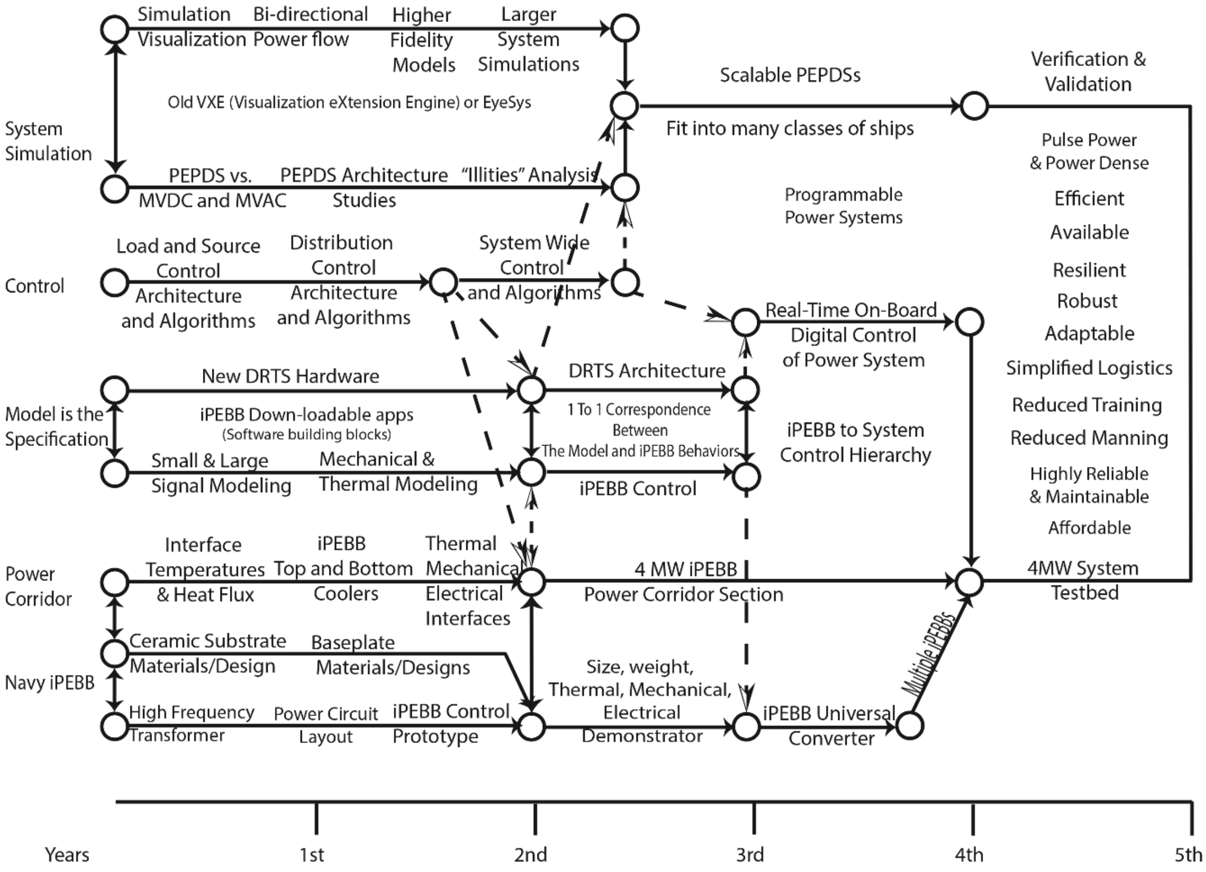


Figure 1 PEPDS Five Year Plan

Introduction

PEPDS will deliver *power and energy management and power functions* to loads. As opposed to the present-day Integrated Power and Energy System (IPES), which uses either AC or DC electrical power distribution, PEPDS is a universal solution, as it can be either AC, DC or both. It will get power from AC and DC sources in the same system at the same time and deliver power to AC and DC loads. PEPDS can control and coordinate many different loads, e.g., motors, pulse power, radar, lasers, and any shipboard load that needs power. It will control and coordinate many different sources too, e.g., turbine generators, uninterruptible power supplies, energy magazines, and flywheels, providing functionality that goes beyond the capability of the Tactical Energy Management (TEM). Consequently, a load need not have to be AC or DC, but it can be of any kind, as PEPDS will provide the power and function that it needs, as well as an integrated system control and health monitoring capability.

PEPDS is far more than an energy and power system. It is a completely new distribution concept and a new class of system. PEPDS includes all the ship's power and energy with control. Using installed storage with inherent storage in iPEBBs, loads, kinetic sources, prime movers, generator sets, UPS, propulsion motors, anything that has power, and sub-microsecond control, PEPDS will provide both point and distributed storage, transient control, and active filtering to assure power and quality of service to all loads—pulsing and continuous.

State-of-the-art medium-voltage dc (MVDC) and medium-voltage ac (MVAC) have energy management algorithms working within classical electrical distribution concepts with slow mechanical devices, like breakers, switchgear, etc. PEPDS on the other hand, as an energy management system, is able to control power flow in every direction using iPEBBs that work together to resolve energy needs and power directives in the nanosecond to microsecond range. Today, bulkheads provide 110V, 220V, 440V, etc. Tomorrow, plugging into the PEPDS will provide many different AC and DC voltages, variable voltage/variable frequency, soft start, overcurrent protection, overvoltage protection, short-circuit protection, current limiting, filtering, health monitoring, pulse power, energy storage, and so much more. As opposed to existing PEBB-based systems such as PNNC and IPNC, connecting a source or load of any type into PEPDS will first recognize the type of source or load, then adjust accordingly its power and control interfaces, and finally perform all the conversions needed. Energy and power are hence tailored to the load and source specific needs, featuring conditioning and filtering to guarantee quality.

PEPDS is also a process for the design and development of shipboard power systems. A process that will be scalable across all power systems in all classes of ships (forward fit or even backfit where applicable). It is envisioned that there will be applications (apps) that can be downloaded into iPEBB. The apps define the functions of the iPEBB and allow manual override for maintenance, testing, and training purposes. What iPEBBs do in a system and how iPEBBs work together in a system defines the PEPDS. Also, iPEBB will learn and make changes during shipboard operation. Therefore, PEPDS will be adaptable.

The envisioned design process can start with the system simulation where the whole system is studied. Areas of interest from the system simulation studies are translated to a Real Time (RT) simulation. The RT simulation is then used to study the areas of interest with greater control and detail, culminating in the development of apps, as well as offering unparalleled training capabilities. Apps are downloaded into iPEBBs. The RTS simulation is also translated, with other RTS simulations, into the Onboard Digital Real Time Controller (OB-DRTC). In time, iPEBB apps, while operating and learning in the shipboard system, can be uploaded to DRTS. The OB-DRTC can be converted back to RTS simulations when needed. DRTS simulations can be converted to system simulations. A new system study can begin.

Cyber security is a process within the PEPDS process. Cyber security and software reliability are critically important in the PEPDS process. There are monitored and controlled interfaces between every step of the process to assure the software implemented is the software certified and the software certified is the software approved. Also, iPEBB apps, changes from learning, and changes from component ageing are captured and conveyed throughout the PEPDS process (creation to implementation, operation to retirement) to assure complete validation, verification, and continued certification. A bidirectional software translation process down from system simulation to iPEBB and up from iPEBB to system simulation assures cyber security.

Cyber security and software reliability are major issues. Malicious software, embedded viruses, can be introduced into a system component, hidden, and later activated to cause system disruptions. Furthermore, failure can result from software design errors, software installation errors, solid-state memory degradation, etc. and cause similar system disruptions. A cyber security/software reliability process from cradle to grave is needed to assure maintainability, reliability, availability, and security.

Background

In the beginning, the Navy's Electric Drive Program worked to replace dedicated propulsion generators, with generators on a common electric bus that could supply power to electric propulsion motors and to all of the loads aboard the ship. This enabled the very large installed propulsion power to be available for high-power sensors and weapons. As a result, a new era of warships was ushered in. In part, this vision has been achieved by the Zumwalt Class and the Daring Class ships. However, these ships used classical electrical distribution systems with slow mechanical components and older power flow concepts, which limit the control of power and energy.

Systems in transition

MVDC, MVAC, and advanced control concepts developed by ONR and NAVSEA will make major improvements in electric warships. These distribution concepts still rely on slow mechanical devices. Advanced control will employ innovative algorithms, but the efficacy is limited by slow devices and lack of distribution system and converter integration - an inferior concept to PEPDS.

Storage

The weapon and sensor systems and the operational paradigms of future warships depend on energy storage. The output impedance of generators limits the amount of power that can be supplied quickly to a system, necessitating storage to support loads that require a large pulse of power. Loads with repetitive pulses also require storage to ensure transients do not disturb other system loads. The performance and efficiency of generation systems can also be improved by incorporating storage to smooth transients. In response to this recognized need for more advanced energy storage technologies, ONR is developing the Hybrid Energy Storage Magazine (HESM). The Energy Magazine is a point storage solution that can be inserted in the system at any location, but its usefulness for loads far from the insertion point is limited by the distribution impedance. More than one Energy Magazine can be inserted into the system to mitigate this problem. The power corridor concept of PEPDS allows the integration of both point and distributed energy storage directly into the power distribution system, not only through the integration of multiple point-storage energy magazines, but also by leveraging the distributed energy storage capacity available within individual PEBBs. A concept is needed that can use the energy storage inherent in the system to enable distributed storage, a more accurate sizing of the Energy Magazine(s), and to compensate for impedances and delays.

Filtering

Filters are needed aboard the ship. Load converters have input filters to help them comply with harmonic distortion requirements as well as to suppress electromagnetic interference (EMI) emissions and improve their electromagnetic compatibility (EMC). Filters are also put in the system to control noise at various points. These filters are passive and have fixed filtering frequencies. Filters can add ground currents that cause other shipboard problems. As time goes on, the system impedances change, operating conditions change, and new equipment is added. As a result, filtering is no longer optimal, and may even be causing noise rather than suppressing it. Furthermore, the capacitors and inductors are large and waste energy.

Active filters could be employed. Like the Energy Magazine, they are point solutions. They are more likely to adapt to changes in the system than passive filters. However, noise location can change due to changes in the system – new equipment, operating conditions, mission and environment changes, ageing, etc. A concept of distributed active filtering is needed which can adapt to system changes, respond to where the filtering is needed dynamically, apply filtering only when and where needed, and reduce the size, cost, and weight of filtering components. The iPEBB concept matches the above filtering needs and could embody the distributed filtering mechanism. In addition, the flexible nature of interconnected iPEBBS will reduce the need for filtering in general by relaxing otherwise rigid terminal requirements between power apparatus. Further, the iPEBB programmability and multifunctionality will enable new capabilities without adding new equipment. As a result, system problems not envisioned today will be solved by creating new capabilities, not new components.

Converters

Converters are needed to control the charging of the storage and the discharge of power to the load. Converters are needed to change the power from the generator to the type of power needed for distribution, and also to change the distributed power type to that needed for the load. Converters are also used in active filters, to control motors, sources and loads. In all, there are many kinds of converters aboard ships.

ONR has been developing converter technologies over the last two decades to reduce the size, weight, and cost of converters. ONR developments, most notably SiC power semiconductors, high frequency power electronics, and novel circuit topologies, are leading to a new generation of converters that are on the verge of meeting the size and weight goals needed for future ships. However, the present custom design practice is a hindrance to reducing costs. MVDC, MVAC, and PEPDS have a common cost and control problem resulting from custom equipment procurement.

Cost

- A manufacturer’s IP practices limit sharing lessons learned and best practices between competing vendors which leads to paying for the same learning cycle over and over from one manufacturer to another.
- Economies of scale are hard to achieve when each converter is specifically designed for a single custom application.
- Advanced tools and design practices that are conducive to long term cost reduction are hard to implement, if these advances cannot be amortized over the number of converters sold.
- The number of converters needed per ship, per application is low. The number of ships built per year can be low.
- The cost of keeping a manufacturer’s team and fab online over the extended shipbuilding years can dominate the cost of the converter.

- Often in the later years of a ship's service, the converter cannot be procured, and a new design and development cycle is needed — no inherent upgrade process.

Control

- Converters are presently part of loads, not part of the distribution system or system control. However, a unified and universal system control cannot be a reality if converters are not part of the distribution system.
- Similarly, a unified and universal system control cannot be achieved if all the converters in the system are from many different suppliers using different control and communication protocols. As a result, system-wide energy management, distributed storage, and distributed filtering would not be possible.

Custom design and development has been the Navy practice from the first converters developed for Navy ships in the 1970s to the present. Changing this practice will require changes in procurement in addition to S&T. Changing procurement practices to include converters in the distribution system will be extremely difficult because it will impact every other shipboard system. It changes everything. However, making the converters part of the distribution is exactly what is needed to reduce cost, achieve control, improve performance, enable cyber security, and further reduce size and weight.

Standards

MVDC, MVAC, and PEPDS all need standard models. The converters for these systems for Navy ships do not exist and will not exist for some time to come. Converters will be custom designed (under the present Navy practice) and they will be far more intricate and detailed than the simpler models now used in the system simulations. The extent of EMI, EMC, nonlinear characteristics, and other artifacts these converters will have, will not be known until they are built. This leads to a circular development cycle, which requires the following:

- A stable system concept to develop converters.
- Standard converter models to design stable system concepts.
- Develop validation and verification (V&V) procedures to standardize converter models.
- Develop converters to validate and verify the corresponding models.

A new standardization concept is needed to break away from custom design practices, as well as a new effective way to standardize converter control protocols and interfaces is needed to enable system wide control and security. iPEBBs, specifically, will aid to achieve these goals as they embody standardized energy actuators by definition, where the constraints of a particular set of iPEBBs prescribes the capabilities of converters comprised of them.

LRU and MCD

Key to developing these goals is the realization of the Least or Lowest Replaceable Unit (LRU) and the Most Common Denominator (MCD). The LRU is the lowest level of component replacement. For example, on a ship, computing devices (laptops, computers, or pads) are replaced when needed, not the microprocessors used in those computing devices. Similarly, the MCD seeks to reduce the number of different parts that make up a system. Ideally, a system made of many parts would only have a single replaceable part type, eliminating the need to have to store and procure many different parts for system maintenance and repair. Users would also only have to be trained to replace and maintain the single part, not many different parts. This implies that this common single part would have to be capable of carrying out all the system functions, leading to an overly-capable part doing the different jobs that much lower cost parts could do in principle. This may seem a disadvantage at first, but economies of scale and high volume procurement would reduce overall costs. This is equivalent to a company having many different computing needs; it would not buy laptops specifically designed for each computing job, but simply seek to select a laptop with the maximum computing needs realizable; buying large volumes and reducing training and procurement costs.

Finding the right LRU and MCD in a system can lead to many system advantages. Supply logistics can be reduced by reducing the number of different parts that need to be procured. Furthermore, by replacing the number of different parts, the number of parts stored aboard ship, the training on parts replacement, and maintenance are reduced. Mean Time to Repair (MTTR) can be reduced by eliminating repair errors like failing to retrieve the right part. Also, a failed controller for vital load can be replaced by a controller from a nonvital load that is nearby. Availability is improved because MTTR is reduced. Reliability can improve because the hardware is produced in volume on automated assembly lines with quality control, and not custom, human-manufactured hardware. In this regard, the cyber security implications of human vs. automated assembly will be investigated.

Control

Today, shipboard electrical distribution control is slow. There are breakers, bus transfer switches, and many such electromechanical devices. They all work in millisecond to second time frames. The source and loads have controllers and converters, which are part of the sources and loads and have minimal control from the distribution system. In PEPDS, on the contrary, controllers and converters are part of the distribution system itself.

Present day distribution system controls utilize many sensors measuring the results of its control actions in an effort to monitor and keep track of the system status and configuration. These sensors are indirectly related to the controlling devices used. PEPDS on the other hand has sensors integrated into every iPEBB, which work directly with their solid-state switches to control power in the microsecond range, exploiting their ability to turn on and off in a few nanoseconds. Consequently, PEPDS embodies a direct control approach where the controlled devices are the control actuators too, where independent sensors are still employed for observability in general; but their numbers can be greatly reduced. PEPDS is hence enabled by the Navy iPEBB, which are multirole power processors that regulate the flow of power in the system, control generator sets, fuel cells, battery energy storage, and all sources of power, as well as controlling all loads. As such, every device that either has or consumes power and energy is controlled.

No control system currently exists for this technology. Network control is the closest. In communication networks, the packets of information are sent all around the net and then assembled at the destination. PEPDS requires control of power and information. Power requires precise timing. The iPEBB controls voltage and current in time. Delays and errors in time can affect the system impedances (ratio of voltage and current), which can lead to errors in power and energy management. To minimize these effects, PEPDS will have to be built using network technology, with architectures, software, and hierarchies created and developed specifically for PEPDS.

Simulation

Non-real-time and real-time simulators are major tools for the design and development of power systems. In a real-time simulation, 1 second in simulation time is 1 second in real time. A machine model in a real-time simulation runs in the same time as the real machine. Real-time simulations can be interfaced with real systems. This leads to many innovative testing, design, and development tools, such as: CHIL

(Controller Hardware In the Loop) and PHIL (Power Hardware In the Loop). Non-real-time simulations can run faster or slower than real time. Non-real-time simulations can run on supercomputers, greatly reducing the computational time for very large systems. These are very powerful tools that are essential for the development and transition of PEPDS to the Navy.

There must be overwhelming size, weight, cost, and performance benefits to justify PEPDS which integrates the system converters into the distribution system. The evidence supporting these claims must be compelling. Modeling and simulation are the only tools available to begin building the evidence needed. Without improved models, simulators, and simulation environments, it may be too difficult and expensive to prototype PEPDS, as it is a completely new electrical power system concept. Accordingly, PEPDS has many more degrees of freedom than MVDC or MVAC, eliminating the need for breakers, switchgear, switch boards, and any other electromechanical device. It simply relies on iPEBB-based PEPDS converters to carry out the multiple distribution system functions; from power flow control and protection to energy management. Hence, assuring the Navy that such a system is reliable and safe will require rigorous analysis and justification, which will in turn need simulators that are 100 to 1,000 times faster, simulators with precise and detailed control, models with greater detail and bandwidth, and simulations with enough component models to capture cascading and synergistic events (at least 2nd and 3rd order electrical, thermal, and mechanical characteristics).

Cyber Security and Software reliability

The PEBB concept transfers hardware design to software design given that PEBBs are programmable. The software programmed into the PEBB, embodied by apps, defines what the PEBB is and what the PEBB does, whereas the hardware defines the limits of what a PEBB can become and what the PEBB can do. However, within limits, software defines everything else. Therefore, cyber security and software reliability are extremely important. Cyber security and software reliability are a part of every one of the five main technical areas.

In the above paradigm, software reliability and cyber security are major issues, especially when malicious software, embedded viruses, can be introduced into a component, hidden, and later activated to cause system disruptions. From higher level system simulations to the iPEBB shipboard operation, creation, development, implementation, and cyber security are continuous processes within the PEPDS process, which will have infinitely more opportunities to implement cyber security in a continuously observable and controllable system in all ships, from the cradle to the grave. Accordingly, research will be needed in cyber security concepts and methods to take advantage of the PEPDS platform to ensure that programming is certified, that there is no embedded malicious software, and that the system performance is reliable. This will add to the existent requirements seeking to minimize the impact and effect of development software design errors, software installation errors, and component degradation.

Aging, breakdown, reliability and safety

The iPEBB and PEPDS must be conceived having in mind that electrical components will age and that even accurate designs cannot take into account the contribution to accelerated aging of defects, change of stresses during operation, change of iPEBB characteristics, and change of mission profiles. Modeling aging and lifetime based on the expected electrical, thermal, mechanical and environmental stresses, is hence one of the legs that can sustain reliable operations.

The above wearout fatigue of iPEBBs and PEPDS will result in slow-changing yet detectable changes in performance that make possible the monitoring of the electrical system for diagnostics and prognosis purposes. PEPDS must become, from this point of view, also an interface able to provide the electrical asset manager (physical or virtual) with dynamic information on its health status, garnering essential information needed for its maintenance and planning. This monitoring function, critical for the system operation, should be fully integrated into the cyber security infrastructure of the PEPDS control and communication system.

Some expected degradation effects due to the wearout fatigue associated to power and temperature cycling includes, among others: wirebond liftoff, thermal impedance increase, and insulation degradation of SiC devices, die attachment and substrates, and encapsulants used in the iPEBB and other power semiconductor modules; delamination and cracking in large area ceramic and organic material substrates; insulation degradation in ceramics; insulation degradation in printed circuit board (PCB) dielectric materials; capacitance degradation in film-type capacitors; increase in resistance and reduced thermal performance in power terminals; insulation and thermal degradation in bus bars and cables; and mechanical wearout in control and communication interconnection terminals.

PEPDS Five-Year Development Program

A five-year program is proposed to develop the Power Electronic Power Distribution System (PEPDS). PEPDS is a new power, energy, and control distribution concept enabled by ONR-developed technology, including high-power-density high-efficiency power electronics, Silicon-Carbide (SiC) power semiconductors, and modeling and simulation design and analysis tools. A 5-year development program is planned as shown in Fig. 1, which illustrates the 5 main areas of science and technology development needed:

- Navy integrated Power Electronics Building Block (iPEBB)
- Power Corridor
- Model is the Specification
- Control
- System Simulation

These five areas are individually addressed below.

Navy iPEBB and Power Corridor Development Approach

The Navy iPEBB and Power Corridor development plan is shown in Fig. 2. These tasks must be executed synergistically. In the past, one would develop the converter breadboard and brass board and then work on the cabinet. The iPEBB is a new integrated converter concept. The Power Corridor is a new integrated power distribution platform. Under the PEBB concept, traditional converter design problems become cabinet design problems, as such their design should be fully integrated. Developing these technologies independently leads to suboptimal results, increased development time, and greater costs. At the end of independent development, one is faced with redeveloping the iPEBB to fit the Power Corridor or redeveloping the Power Corridor to fit the iPEBB. The Navy iPEBB and Power Corridor are thermally, electrically, and mechanically interconnected. Since both technologies are extremely sophisticated, redevelopment of either will be costly; hence the greatest benefit is gained from coordinating their development.

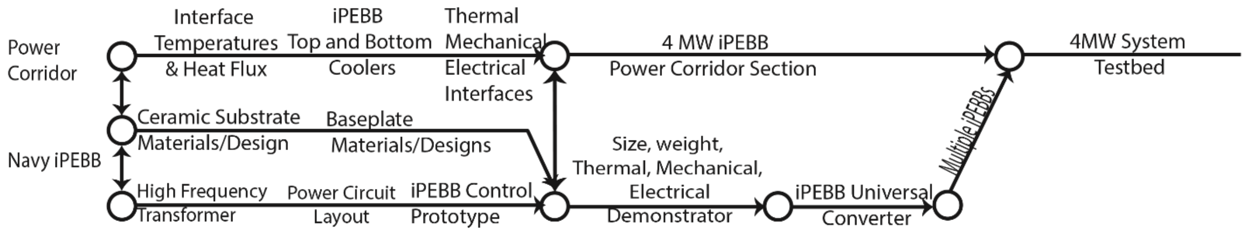
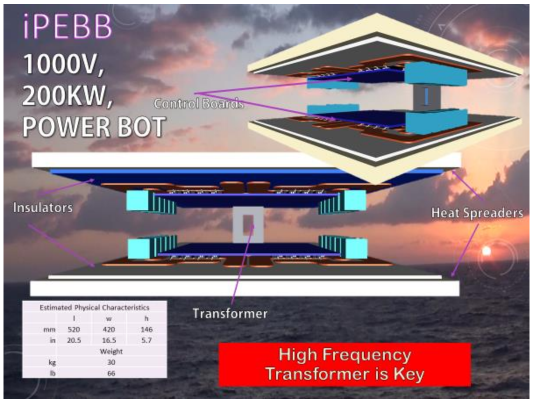


Figure 2. Plan for the Navy iPEBB and Power Corridor

Navy iPEBB

The Navy integrated PEBB (iPEBB) is an MCD and an LRU. The iPEBB concept will enable increased manufacturability, power density, efficiency, and flexibility, among others. The iPEBB is the result of over two decades of ONR development on power semiconductor technologies and materials. Many of these developments have transitioned to industry and the Navy. The Navy iPEBB shown in Fig. 3 is under development and very close to meeting the minimum goals needed by PEPDS.



Estimated Physical Characteristics			
	l	w	h
mm	520	420	146
in	20.5	16.5	5.7
	Weight		
kg	30		
lb	66		

Figure 3. Navy iPEBB rendering based on 2019 development results.

A twofold reduction in iPEBB weight is needed for sailor handling. The shipboard size goal is dependent on PEPDS developments. The PEBB1000 (1,000 V) and PEBB6000 (6,000 V) are currently being investigated. The PEBB1000 had transitioned to the ONR Navy iPEBB development program and is the first PEBB to enable a 100 MW ship set. There is still the question of 1,000 V vs. 6,000 V PEBBs for 35 MW and higher power converters, as the electrical resolution of these units ultimately determines power quality, EMI, controllability, cooling system needs, reliability, and the wearout fatigue and lifetime of these components. These tradeoffs must be further investigated.

It would take an estimated 5,000 iPEBB1000s for a 100 MW ship set. The number of iPEBB1000s does support higher volume, lower costs arguments. The high voltage PEBB6000 would decrease part count reliability by reducing the number of units in a ship set. However, the PEBB6000 today is larger and could potentially be too heavy for a single sailor to handle. Research is needed to determine optimum unit sizing 1,000 V, 2,000 V, 6, 000V, or other size PEBBs.

Another key development needed is a 1-to-1 correspondence between the model and the iPEBB behavior. It is planned that control will be by apps downloaded into the iPEBB. A guarantee that the iPEBB will perform exactly as its model predicts, within tolerances, enables the “Model is the Specification” concept, which encompasses the notion that the model is the control and the machine itself. This is necessary for the Navy to move away from custom converter design, to decouple converter design from system design, and to enable standards that yield lower costs and can achieve a greater performance.

Another key development is the containment of all the high frequency switching artifacts, EMI, EMC, etc. within the Navy iPEBB. If these details can be contained within the Navy iPEBB, then the iPEBB model in a system simulation can be simplified. Models used to design iPEBBs will have to consider all the details – EMI, EMC, with all the traditional thermal, mechanical, electrical design practices. The system models will not have to consider these details. If the Navy iPEBB can be manufactured to behave like its model, and if the non-linear characteristics of every shipboard load and source can be controlled and eliminated by its Navy iPEBB, then ship simulation models can be simpler and many more models and details can be added to the system simulation. However, a key challenge remains in the expected aggregation of iPEBBs to compound large power converters, where switching between iPEBBs will generate fast switching events equivalent to those of non-PEBB-based converters performing the same function. EMI and EMC will hence have to be ensured at the system-level (iPEBB cluster), where the inherent active filtering of iPEBBs may be used to compensate for the secondary level of conducted and radiated emissions.

Finally, the Navy iPEBB will be guaranteed to work equal to its iPEBB model and the system simulation will work as desired with iPEBB models, then the shipboard system will work as desired with Navy iPEBBs. This enables a certainty of shipboard performance never possible. This also enables accuracy and precision in assessments and tradeoffs, which is an essential step for Cyber Security in shipboard power systems.

Working with the digital real-time simulation (DRTS) tasks, the iPEBB control will be developed to enable app-based programming. Furthermore, the iPEBB will be capable of conveying changes from health monitoring and learning to higher levels of control and software development.

At the end of the second year, prototype Navy iPEBBs will be produced. During the 3rd year, an iPEBB-bsaed converter demonstrator will be built to verify and validate that all the EMI, EMC, control, thermal, mechanical, and electrical developments, and that all design loops are closed. At the end of the 3rd year, the results from Control, Model is the Specification, and the iPEBB demonstration will be used to design and build the Navy iPEBB Universal Converter.

Substrate and Baseplate

The iPEBB is a new form factor for integrated power converters. It has two large cooling surfaces – top and bottom, each as much as 357 in^2. There are several multidisciplinary research issues:

- Increasing voltage
- Increasing power rating
- Increasing thermal performance
- Increasing mechanical performance
- Managing thermal coefficients of expansion.
- Ensuring effective insulation design, specified life and reliability

Over the first 2 years, the substrate and baseplate materials and designs will be investigated. Toward the end of 2 years, the substrate and baseplate are joined to form the foundation of the iPEBB. Although each investigation has its own objectives, the joined system must have good thermal spreading, good thermal cycling performance, and good mechanical support. The work must be performed cooperatively to assure the system succeeds. The work has many layers of multidisciplinary tradeoffs.

Ceramic Substrate

20 kV DC/13kV AC is a PEPDS goal. An iPEBB would have to be able to withstand 80 kV impulse (transient) and 40 kV steady-state testing for this goal. The ceramic substrate or new material would have to withstand this testing and still have very good thermal transfer characteristics to cool the iPEBB internal components. Increasing thermal performance leads to higher current and power per PEBB, which affects the semiconductor chip size and cost. Increasing PEBB voltage decreases current and heat losses for the same power – also affecting the semiconductor chip size and cost. Increasing voltage also increases thermal resistance, which decreases the power per iPEBB.

Baseplate

The iPEBB baseplate also needs to have good thermal characteristics. It also must provide good structural support. Bending leads to cracked ceramic and delamination. Increasing base plate thickness enables more support; but increased base plate thickness increases thermal resistance and weight. Tradeoffs and new materials will be investigated, and new baseplates will be designed.

Thermal Spreading

The iPEBB has two large cooling surfaces. The present ceramic and base plate materials cannot take advantage of these large surface areas, which will require new thermal spreading concepts and materials to be developed and integrated into these components. This would also impact larger integrated power modules such as the PEBB6000, possibly enabling size and weight reductions.

Thermal Coefficient of Expansion (CTE)

The iPEBB consists of multiple materials joined together. The compatibility and bonding of these materials is critical for the reliability and effective thermal management of the iPEBB. For example, if the CTE of the substrate and baseplate are mismatched, delamination could occur at the bonded interface, resulting in increased thermal resistance. Thermal spreading materials could be buffers against cycling degradation or could make the problem worse. Research is needed to understand the physical properties and tradeoffs involved, and to explore bonding materials and methods for the joining of large areas with low thermal resistance and high reliability. Otherwise the lifetime due to power and temperature cycling of all components could be severely limited.

High Frequency Transformer and Power Circuit

Increasing the switching frequency of the iPEBB power circuits has resulted in dramatic reductions in size and weight of passive components leading to improved integration. This work will explore the limits of switching frequency and resulting size and weight reductions. Furthermore, integration of the transformer with the power circuit will be investigated to optimize size, weight, power, electrical, EMI, and thermal performance.

High Frequency Transformer

Transformer integration with the power circuit is a key investigation. The transformer electrically isolates the distribution side from the load side of the iPEBB. The transformer is also mechanically and thermally connected to both sides of the iPEBB. High-frequency transformer technology is key to meeting the iPEBB size and weight goals. As the operating frequency of the iPEBB increases, the size and weight of the passive components, such as inductors and capacitors, decrease. ONR’s iPEBB development program has enabled several orders of magnitude of size and weight reductions of the passive components, enabling highly integrated power circuits. Further reductions and integration are expected with research in 500 kHz and above switching frequencies. The impact of vibration, shock, thermal cycling, cooling, and mounting on the transformer design will also be investigated. New electrical insulation, which must be as thin as possible, resistant to degradation phenomena like that resulting from partial discharges and space charge, and also meet the specified life and reliability targets, will be developed.

It is important to keep the distribution side and the load side of the iPEBB identical and reversible for manufacturing and shipboard application reasons. If the iPEBB has sides (top plate and bottom plate) that are the same, then there is no difference in manufacturing processes for the two assemblies, which leads to high volume and lower production costs. If both sides are the same and the iPEBB is reversible then insertion into the shipboard system can be simplified, and repair time and mistakes can be reduced.

Power Circuit

Miniaturization of power components leads to increased power circuit integration that can lead to lower size, weight, and cost. Miniaturization also leads to increased power density which increases the thermal problem. Improved thermal spreading technologies will help this problem. Increased power circuit layout area can also help thermal spreading. However, increasing power circuit layout area leads to increased circuit impedances creating more filtering problems and losses. As the power circuit components become miniaturized, many more options for layout emerge. As the power density increases thermal and mechanical problems also emerge. On the other hand, as the voltage increases, increases in standoff distances between components are required to limit the electric field, which can lead to increased layout area. Moreover, salt accelerates corrosion and worsens voltage isolation requirements. Electric field control, dielectric materials and coatings, inert gasses, and hermetic sealing are options that could be explored. The iPEBB power circuit is a multi-disciplinary, multi-tradeoff design problem. The iPEBB is pushing the boundaries of power density and miniaturization, which will require the development of new materials, tools, and methods for the design of power circuits.

iPEBB Control

This is a major new area of research, which should be coordinated closely with the new DRTS hardware and software research. The success of this work impacts the Model is the Specification realization and the implementation of cyber security. There are four areas of development: Control, Health Monitoring, Learning, and Cyber Security itself.

Control

The first research problem is to develop prototype iPEBB hardware and software. The second research problem is harmonizing the iPEBB hardware and software with the real-time simulation hardware and software. The iPEBB control and DRTS do not have to be exactly alike. There only needs to be a one-to-one correspondence between simulation and real behavior. The third problem is to create control apps. Control apps are to be downloaded into the iPEBB, offline and during system operations. Change to apps must also be up loadable to the DRTS platform—even during shipboard operation. Uploading and downloading apps between the iPEBB and DRTS is critical to assuring that the model and machine are the same. This is critical to cyber security to monitor changes and assure that changes in performance are not due to malicious software.

Health Monitoring

This area has as goal the monitoring of the iPEBB health, as invariably there will be changes in the iPEBB components due to ageing and environmental stresses. These changes will change the behavior of the iPEBB that could ultimately lead to failure. Monitoring these changes is important to understand the difference between controlled changes in behavior and changes due to degradation. In turn, knowing the health of the iPEBB is important for estimating PEPDS state for planning maintenance and mission readiness. Strategies will be investigated such as onboard look-up tables with baseline characteristics that can be compared to real-time, in-circuit measurements. Methods for transmitting this data to the OB-RDTC will also be investigated.

Also, the online real-time health monitoring system should be able to perform diagnosis and prognosis down to the power device level. The desired functions include self-acknowledgement, gate drive connection verification, power device status diagnosis, gate dielectric wear out detection, device degradation and prediction. The monitoring system can detect abnormal conditions that occur either within gate drive circuits and their driven power devices.

Learning

There will be changes in the control apps made by the iPEBBs themselves as they learn during their operation. Learning is important for a ship that will be in service for 30 to 50 years. PEPDS cannot be designed a priori to every possible mission event and environmental change over long periods of time. With iPEBB learning, PEPDS will be capable of adapting to missions and environments. With health monitoring and learning, the PEPDS process will be able to continuously upgrade the system design and prepare for scheduled repair. Methods and tools for iPEBB learning will be investigated.

Cyber Security

Cyber security, software reliability, and hardware reliability have the same goal – to detect harmful changes that could lead to harmful system performance (prognostics and diagnostics). Cyber security has an additional problem of malicious code gathering information on the system, which could be passed to an agent for harmful intent. PEPDS integrates all the power control and monitoring in the ship into one system. This will give PEPDS enormous warfighting capability. Being able to control or cause the failure of PEPDS would be a warfighting advantage to an enemy. Being able to know the status of PEPDS (for example: vulnerabilities at specific times) also enables a warfighting advantage to an enemy.

Knowing the changes due to aging/stress and in-service learning help to narrow the possible causes for a pending failure. Control, health monitoring, and learning (in nanoseconds to microseconds time frames) enables cyber security to be precise, accurate, and timely in detection and prediction of malicious events.

Demonstrator

The Navy iPEBB demonstrator is a key event in the program. HIL testing of the demonstrator will be performed to confirm iPEBB control, DTRS modeling, noise performance, and apps. Failing in these objectives would be grounds for ending or making major changes in the program.

Power Corridor

The power corridor incorporates in a single modular entity all the components of the electrical distribution system for the main bus power throughout the ship: main bus cables, conversion, protection, isolation, control and energy storage. This modular unit incorporates many advances to the design, construction, operation and maintenance of the electrical distribution system as a whole. A few are presented here:

- In the very early stages of design, the power corridor is reserved space in the ship design, incorporating the functionality and space requirements of this system that has become the lifeblood of a naval ship's warfighting capability. While modular in design, the power corridor enables full customization at the watertight subdivision level, tailored to the sources and loads in that section.
- The power corridor is created from modular repeated units that are constructed and tested off-hull in a more spacious and cleaner environment, then lifted into place as an assembly for final installation and connection. Plug-in connections between sections of the power corridor and between the power corridor and both sources and loads improve the ease of construction, maintenance, repair, upgrade and alteration of the system and the customers it supplies; further, plug-in connections create a simple method for casualty power.
- The power conversion and distributed energy storage features of the power corridor are accomplished using the iPEBB as the least replaceable unit (LRU). Each identical iPEBB is sized such that it can be carried through a ship's passageways by a sailor and can be easily installed by sliding into place and locking, with no additional connections required, e.g. for cooling, power, data, or control. Thus, instead of several bespoke large power converters, there will be hundreds of identical units with the attendant logistical savings such as reduced cost, ease of replacement, installed spares, reduced training, etc.
- In addition to the energy storage inherent in the iPEBB, larger stores of energy in the form of energy magazines can be incorporated directly onto the main bus. This energy storage can support not only nearby special-purpose needs such as pulse-load weapons or sensors, but can also be sized to facilitate in-port battery operations, single-generator operations in port and underway, and energy-efficient management of ship operations.
- There are a number of advantages from the perspective of resiliency. All supporting (serial) electrical components are co-located, while there is geographical separation of redundant (parallel) electrical components in multiple corridors. The corridor is designed for soft power degradation such that the failure of a single component does not take down the entire capability.
- The power corridor also improves sailor safety by locating essentially all electric connections, protection and power conditioning equipment in a highly defined, enclosed space away from any chance for unintended exposures.

Steps to a Prototype

One goal of this project is the construction of a prototype power corridor segment that serves as a viable demonstration of the technology and as a test facility for the PEPDS concept. Achieving a megawatt-level prototype in five years depends on the close collaboration between the power corridor and iPEBB design development, as iPEBB-based power converters configured within the corridor will compound an integral electromagnetic, thermal and mechanical operational domain. A five-year plan for developing and building a prototype devotes two years to develop the needed science and technology, two years to building a working prototype, and one year to test, debug and improve the prototype. This process must begin with a scoping session among the full team to clearly delineate the goal, detailing such parameters as target power level, voltages, source and load types, etc.

The science and technology development areas to support this goal require power-corridor-level research in five areas:

1. investigation into ship design and construction impacts at the macro scale including high-level design of corridor elements and connections between them and an energy storage plan;
2. thermal management of the heat generated from system operation;
3. design of the physical interfaces between the corridor and the iPEBB including electrical, thermal, mechanical, structural, and data/information connections as well as a reliable iPEBB connection, injection, and ejection system for sailor-safe replacement and repair;
4. corridor internal design including assembly of multiple iPEBBs into a single converter; and
5. control at the corridor level.

Each of these areas are explored in what follows. The research into these aspects of the corridor must be accomplished in conjunction with design of the iPEBB so that the tradeoffs of the thermal, mechanical, and electrical considerations within the iPEBB and within the Power Corridor are coordinated for proper design and material choices. The power corridor must have high availability and absolute safety. As a result, this is a very challenging multi-variant and multidisciplinary research area.

Ship Design and Construction Impacts

A core power corridor assumption is that all the major power-handling elements of the power distribution system are to be located in reserved space allocated in the early stage of the ship design. Further, these elements are co-located in a modular assembly that can be constructed and tested off-hull, then lifted into place. These assumptions have significant ramifications in ship design and arrangement, ship structural design, and electrical system reliability, robustness and resiliency, some of which are enumerated below. Ship design studies under various constraints (various ship sizes, power levels, mission system combinations, etc.) will elucidate the following considerations:

Reserving space for the power corridor changes the paradigm currently used in early-stage design of Navy ships, potentially reducing the space required inside the machinery rooms but also potentially reducing flexibility in placement of non-power-corridor equipment. Investigations into arrangements must include access for maintenance, repair and upgrade. Considerations for sailor safety will also affect arrangements.

The power corridor could become a structural component of the ship hull, incorporating the support normally provided by large longitudinal girders. The design of the power corridor, especially the number, location and length of the corridors, should be analyzed in conjunction with the potential reduction in structural steel required elsewhere.

The power corridor concept includes the vision of modular segments that can be assembled into a full corridor; each watertight subdivision contains a power corridor segment that is assembled from these modular segments. Design of the elements that make up a segment and typical segments needed by a variety of ship types requires investigation.

The power corridor incorporates modular energy storage in the form of discrete units such as the energy magazine and in the form of distributed storage available within each iPEBB. The sizing and use of this energy storage and its availability to mission systems with various requirements in terms of ramp rate, cleanliness, pulsiness, etc., can impact both the corridor and the iPEBB design.

Improvements in the construction process are envisioned, for example, by employing off-hull construction and testing of unitized elements to enhance reliability while providing a means for cost reductions.

Thermal Management

Investigation of emerging iPEBB thermal concepts is needed to understand the cascading effects on the Power Corridor materials and design – PEBB level to Corridor level to ship level. Results from these investigations will be iterated back into the Navy iPEBB investigations. This cycle is expected to continue until all the investigations converge on a final set of solutions for the Power Corridor, the Navy iPEBB and the ship.

While the thermal management problem at first blush seems fairly straightforward in that the amount of heat generated by a single iPEBB and the surface area available for heat dissipation on that iPEBB provide a heat flux that is not extreme, there are two constraints that make this a challenging problem indeed: first, there are no liquid connections allowed to the iPEBBs themselves, so direct liquid cooling of the units is prohibited; and second, the units are intended to be easily changed out by the ship's crew while the ship is underway, so the units must be compact, light-weight and robust to physical damage, precluding a large finned air-to-air heat exchanger. This makes the heat removal from the iPEBB to the corridor a challenge as many of the current technologies available for electronics cooling are obviated by these constraints.

The greatest challenge in heat removal in this project is crossing the surface of the iPEBB. Direct contact heat exchangers employing conduction between the hot surface and a cold plate require full contact across the entire surface. Ensuring contact over such a large surface is nearly impossible; such prospects as grit lodged between surfaces, mis-alignments of planar surfaces, or deflections of the surface from truly planar, measured by TIR (total indicator reading) flatness requirements, are a few potential obstacles. Many power modules today employ a "bowed" base plate that is forced flat when bolted to the heatsink cooling surface to ensure good contact; however, the iPEBB will not be bolted to the cooling surface, merely latched in place. Thinner heat transfer surfaces, another potential technology, are susceptible to bending.

Heat transfer by conduction can be enhanced through contact enhancers such as thermal paste; however, paste can form voids that lead to reduced thermal spreading, hot spots, and lower long-term reliability. Accurate use of these contact enhancers is counter to the PEPDS concept since it would increase the expertise and thus the sailor training required to replace iPEBBs. While the goal is for the iPEBB swap-out process to be simple and quick, it is also the goal that the PEPDS reliability should be very high such that most iPEBBs will remain in place, untouched, with no maintenance required, for long periods of time. The use of thermal paste does not support either of these goals.

Research is needed to develop a new iPEBB cooling paradigm and to develop materials and designs for the top and bottom coolers and their interfaces with the power corridor.

While heat transfer out of the iPEBB to the corridor is a significant challenge, there is also the challenge of the heat removal from the corridor to the ship's cooling system. The corridor design includes many iPEBBs combined to create higher-voltage and higher-current power converters, thus placing several heat-generating components in close proximity. Design of this component arrangement, considering the iPEBB cooling process developed, will be required as well.

Thermal, Mechanical, Electrical and Data Interfaces

As mentioned previously, the design of the iPEBB and the design of the Power Corridor must proceed hand-in-hand; the design loop must be closed so that iPEBB interfaces can be defined.

Electrical interface

Electrical connections are a serious safety issue and, as a result, are a major maintenance issue. Connections can loosen over time due to ship vibrations; loose connections heat up and cause fires. To prevent this, connections are inspected frequently, demanding significant time from the ship's crew. The power densities envisioned for PEPDS intensify the seriousness of this safety concern. While welded connections are a solution to the loosening problem, welded connections do not allow reasonable, timely, and easy repairs and do not fit with the PEPDS concept. Another solution must be found.

iPEBB electrical connections must be quick-connect/disconnect to support availability goals. Similarly, larger-scale quick-connect/disconnect electrical receptacles for connecting large sections of the power corridor itself will facilitate the modular nature of the corridor and can provide a new capability for casualty power. Although quick-connect/disconnect electrical connections exist that are approved for Navy shipboard use, they are not at the voltage or power levels required for this application. Further research and development are required.

Further, while the iPEBB itself is designed to contain all switching artifacts and electromagnetic signatures within the unit, the aggregation of iPEBBs as functional (and larger) power processors will be a source of EMI emission by itself; hence their interconnection and the connections from the power corridor to the iPEBBs (including cables routed within the corridor) must be designed to minimize ensure the EMC of the power corridor itself. The use of the iPEBB active filtering capacity may become crucial to achieve this goal.

Safe replacement of the iPEBB units must address the voltage and current levels within the corridor during swap-out. The methodology for changing iPEBBs must include processes for ensuring sailor safety and safety of the equipment from stray power flows. This process must be integrated into the control structure of the corridor, and must hold up under casualty and damage scenarios.

Thermal interface

The top and bottom plates of the iPEBB are designed to be thermal interfaces. The coolers, their cooling surfaces, and the junction between coolers and the iPEBB, must trade off easy iPEBB withdrawal and insertion, high thermal conductivity, and good heat spreading characteristics. Details of the thermal interface challenges were described above.

Structural and mechanical interfaces

The iPEBB is designed to be easily snapped into place and locked down. Design of the structural portion of the cabinet to include the mechanism for locking iPEBBs into place when inserted and facilitating removal when ejected is required. It must also enable the electrical, thermal and data connections to be accomplished during the insertion process, maintained while the iPEBB is in place, and disconnected when the iPEBB is ejected, with no intervention by a person beyond the initial placement of the iPEBB unit itself. Further, these connections must remain linked on an active ship, underway, despite shock, vibration, temperature changes, atmospheric conditions, salt air, etc.

Data interface

The data connection must be automatically completed and must provide a clean connection that is impervious to cyber intrusion. This data connection must be integrated into the control system, sending a signal to the control systems to initiate the programming of the iPEBB once in place and the subsequent powering-up of the iPEBB for employment in ship power system operations. This interface with the control system must also power down the iPEBB prior to removal.

Converter design

The connectivity of components within the corridor requires research and design. iPEBBs in a corridor must be arranged such that multiple iPEBBs work together to achieve conversion functionality at higher voltages and higher currents than can be handled by a single iPEBB. Connectivity between these converters and the bus cabling, sources and mission systems must be accomplished in a manner that mitigates or preferably eliminates EMI and EMC issues, allows re-configuration in response to operational needs including casualty, and provides adequate flexibility. Further, the design of filtering, grounding, and other electrical considerations must be determined at the corridor level.

Power Corridor Control

This is a major new area of research. A PEPDS principle is that all iPEBBs are interchangeable and independent of their input and output orientation, location in the Power Corridor (location in the distribution system), and the source or load connected. This requires that iPEBB apps are downloaded into the iPEBB after it is installed into the Power Corridor. This work must be coordinated with new DRTS hardware and software research. The success of this work impacts the Model is the Specification and implementation of cyber security. Like the Navy iPEBB, there are four areas of development: Control, Health Monitoring, Learning, Cyber Security. The results of this work will be added into OB-DRTC investigations and the development of the Control Hierarchy from iPEBB to System.

Control

Like Navy iPEBB control, the problems are to develop prototype Power Corridor control hardware and software, harmonizing hardware and software with real-time simulation hardware and software, and then create control apps. There needs to be a one-to-one correspondence between simulation and real behavior. Like the Navy iPEBB, control apps are to be downloaded into the Power Corridor, offline and during system operation. Also like the Navy iPEBB, change to apps must also be up loadable to the real time simulation platform. Uploading and downloading apps between the Power Corridor and real-time simulation is critical to assuring that the model and machine are the same. This is critical to cyber security to assure that changes in performance are not due to malicious software.

Like the Navy iPEBB, a control hierarchy that includes the Power Corridor must be developed. Also, a concept of Power Corridor control needs to be developed. In addition to programming iPEBBs, Power Corridor monitoring and control will be investigated. Active thermal-management control will be developed. Control and monitoring of mechanisms for inserting and withdrawing iPEBBs will be developed. The Power Corridor must keep sailors safe and provide a means to prevent sailors from electrical, thermal, and mechanical harm.

Health Monitoring

Methods to monitor the health of the Power Corridor will be investigated. Like the Navy iPEBB, there will be changes in components due to ageing and environmental stresses – like electrical connection degradation. These changes will change the behavior of the Power Corridor and ultimately lead to failure. Like the iPEBB, monitoring these changes is important to understand the difference between controlled changes in behavior (though apps, malicious code, learned changes) and changes due to degradation. Knowing the health of the Power Corridor is important for estimating PEPDS state for planning maintenance and mission readiness. Like the iPEBB, strategies such as onboard look up tables with baseline characteristics that can be compared to real time in circuit measurements will be investigated. Methods for transmitting this data to and from the OB-DRTC will also be investigated.

Learning

Learning is important for a ship that will be in service for 30 to 50 years. PEPDS cannot be designed a priori for every possible mission event and environmental change over long periods of time. Like the Navy iPEBB, Power Corridor learning enables PEPDS to adapt to missions, environments, and aging. With health monitoring and learning, the PEPDS process will be able to continuously upgrade the system design and/or prepare for scheduled ship repair. Methods for Power Corridor learning will be investigated.

Cyber Security

Since the Power Corridor will have control hardware and software, cyber security, like the iPEBB is critical. Cyber security has the problem of malicious code gathering information on the system which is passed to a harmful agent for harmful intent and/or malicious code activated to cause harm. PEPDS integrates all the power control and monitoring in the ship into one system. This will give PEPDS enormous warfighting capability. Being able to control or cause the failure of PEPDS would be warfighting advantage to an enemy. Being able to know the status of PEPDS (for example: vulnerabilities at specific times) also enables a warfighting advantage to an enemy.

This work contributes to System Control Hierarchy. Control at the Power Corridor and the OB-DRTC levels will define control layers above the iPEBB application layer and provide additional partitioning opportunities for cyber security processes.

Model is the Specification

Specifications based on models is a concept unique to ONR. A model is not static like paper standards. It is dynamic. It can be simulated. A model can be tested in ways not practical or affordable using physical methods. Models can be real time and work with real machines. Models can be non-real time and used for searching novel ideas. There is a lot of talk about digital design and development, virtual prototyping, and so on. Most of these concepts underestimate the detail and computational intensity. Furthermore, these concepts are often thought of in the context of a single technical discipline. This is fine if one can ignore mechanical and thermal aspects in the design process and succeed by only considering electrical.

Power systems must consider thermal, electrical, and mechanical characteristics throughout the design and development process. ONR has developed many power-system and power-converter modeling tools over the last 25 years. In the real-time domain alone, there are: High-Speed Real-Time Simulation, Hardware In the Loop (HIL), Controller In The Loop (CIL), and Power Hardware In The Loop (PHIL) -- machines, methods, and mathematics. ONR has developed the only cross-discipline design tool – S3D. The time is right for “Model is the Specification”. Research is needed to develop thermal, electrical, and mechanical models that can be synchronous, cross-connected, and hierarchical.

The work proposed is shown in fig 4. Over the first 2 years, real-time models and modeling will be reexamined for PEPDS design and development. In parallel, new DRTS hardware will be developed to run these models in real-time at 10 to 100 times higher simulation speeds than existing systems. Model fidelity will be much greater and system simulations will have many more models. Furthermore, it is the very core of this program to create a 1-to-1 correspondence between DRTS and iPEBB control. This is foundational for cyber security, reliability, and affordability. A revolution in DRTS technology is needed to accomplish all this.

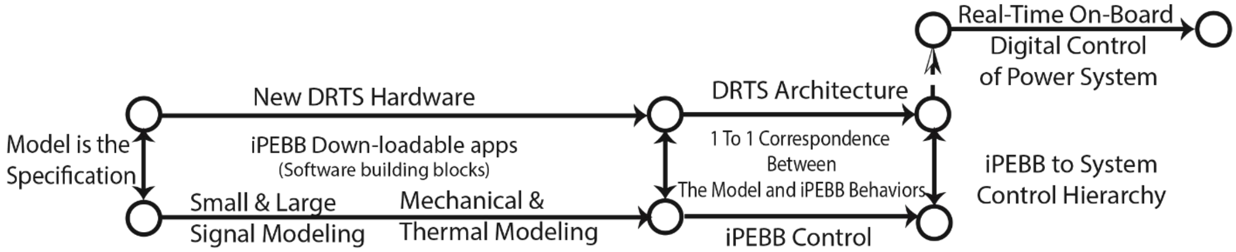


Figure 4. Tasks for Model is the Specification

Navy iPEBB and the Model is the Specification

The Navy needs a standard-based design process. Unlike standards of the past, technologies are emerging from ONR's PEPDS and ESRDC programs that will enable models to be the standards for future Navy equipment. The final S&T goal is to complete the tools and methods to realize a Navy iPEBB that can be manufactured to keep all the nonlinear phenomena within the converter (or within a tolerance that results in the converter artifacts being insignificant to the system performance), then high frequency switching and associated non-linear phenomena, such as EMI EMC, from converters are not system problems. This, however, is bound by the type of power conversion function to be conducted by a given group of iPEBBs, which may impose fast switching transients at the converter level while iPEBBs may still be able to withhold EMI emissions within their structure. The system converter performance is then defined by a much simpler model. An app is downloaded into the converter and the converter behaves like its model. "The model is the specification; the model is control; and the model is the machine".

As stated in the introduction, MVDC, MVAC, and PEPDS all need standard models. The converters for these systems for Navy ships do not exist and will not exist for some time to come. Converters will be custom designed (under the present Navy practice) and they will be far more intricate and detailed than the simpler models now used in the system simulations. The extent of EMI, EMC, nonlinear characteristics, and other artifacts of these converters will not be known until they are built. We are in a circular development cycle requiring the following:

- A stable system concept to develop converters.
- Standard converter models to design stable system concepts.
- V&V procedures for converter models.
- To develop converters matching verified and validated models.

If "the model is the specification, the model is control, and the model is the machine", then V&V is achieved. If the Navy iPEBB is guaranteed to work equal to the iPEBB models and the system simulation works as desired with iPEBB models, then the shipboard system will work as desired with Navy iPEBBs. Converter design is decoupled from system design; and the cycle resulting from custom converter and system design practices is broken.

Although, iPEBB models are the main challenge. Sources, passive components, loads, and all other system elements must also have standard models. Models must have thermal, mechanical, and electrical characteristics. These models must also have higher fidelity characteristics. There must be a 1-to-1 correspondence between the model of any component and its behavior in the shipboard system.

iPEBB Downloadable apps (Software Building Blocks, concept proposed by Belkhayat of HII)

As stated in the background, real-time simulation is not, today, directly related to converter control. Today, they have different purposes, processes, and platforms. In real-time simulation, models are run in real-time and real-time simulations can be interfaced to real systems. This leads to many innovative testing, design, and development tools – such as: HIL, CIL, and PHIL. However, DRTS does not care about the actual hardware and software within the controllers they are simulating. This work will develop a real-time simulation platform that directly relates to the iPEBB control platform. A 1-to-1 correspondence between the real-time simulation and iPEBB behavior is to be established.

At the end of two years, thermal, mechanical, and electrical models will be combined with control models, the results of iPEBB, and Power Corridor tasks to form Software Building Blocks. The New DRTS hardware and Software Building Blocks will be used to build a new DRTS system which will be exercised to create iPEBB control apps and to simulate PEPDS.

Small & Large Signal Modeling

Work is needed to reexamine models and model partitioning. In the iPEBB task, high-frequency artifacts and switching nonlinearities of the conversion process are to stay within the iPEBB. System iPEBB models can be decoupled from the models used to design iPEBB. Sources and loads will have their own low and high frequency artifacts. In the iPEBB task, active filtering capabilities will be developed. The distribution system will be controlled and filtered by iPEBBs. Sources and loads will be filtered by iPEBBs. Models need to be reexamined in the light of their interface with iPEBBs and their application in PEPDS. In this task, investigations of small and large signal modeling concepts will be performed to redefine and partition modeling criteria and models for real-time simulation – including components such as generators, fuel cells, inductors, capacitors, and all PEPDS components. System Simulation investigations will build on the results of this work.

Mechanical & Thermal Modeling

New mechanical and thermal models are needed for integration with the newly defined small and large signal models. Thermal and mechanical models are needed for motors, generators, pulse power equipment and other power system components. Mechanical vibrations can be a source of noise. Mechanical fidelity is important for the development of filtering algorithms. Thermal fidelity is important for the development of component safe operating areas and thermal management control. The fidelity of thermal and mechanical models is important for the study of stresses that must be understood for design of iPEBB, the Power Corridor, and PEPDS.

New DRTS Hardware

New Digital Real Time Simulation (DRTS) hardware is needed to study higher frequency iPEBBs and to increase the number of models that can be simulated concurrently. In the past, ONR has developed simulators based on DSPs and FPGAs. ONR has continually pushed the state of the art in simulation speed and the number of simultaneous equations simulated simultaneously. The new PEPDS challenge integrates new models, model partitions, with mechanical and thermal characteristics and high-frequency electrical characteristics. A revolution in DRTS hardware is needed.

Hardware is ever evolving. Investigations are needed to determine limits of DRTS development possible in this program. An investigation of new computational devices, such as graphic processors, will be performed. ONR has been the leader in developing DTRS platforms with different computation devices where each device is optimized for the type of calculation performed in the simulation. At the end of two years, results of DTRS hardware development will be available to develop a new DRTS Architecture and build a DRTS capable of simulating PEPDS real-time models and generate Software Building Blocks.

Simulation Speed

Real-time simulations must be faster than the fastest artifact in the system to capture all the characteristics of the system. Voltage spikes can lead to system failures. EMI and EMC can cause errors in control, which can lead to system instabilities and failures. Navy iPEBBs will keep its EMI and EMC within its package. However, the Navy iPEBB under development will have switching frequencies 10 to 100 times faster than the converters being simulated today. Real-time-simulation technology is 10 to 100 times behind that needed for the Navy iPEBB and PEPDS.

This task will establish the state-of-the-art in high-speed real-time simulation by concurrently examining the mathematics and computational partitioning with the new DTRS hardware developments. Mechanical, thermal, and electrical phenomena have different time constants. Methods, such as multi-rate simulation, need to be investigated to optimize real-time simulations and increase simulation speed.

DTRS Architecture

The results from the small and large signal modeling, mechanical thermal modeling investigations, DRTS hardware, and simulation speed will be studied to develop the deployment of computation assets in the simulation platform. For example, real-time simulations that include mechanical and thermal characteristics would likely require multi-rate simulation techniques which could be implemented concurrently on different computational devices. A new real-time hardware simulation architecture will be defined that is greatly expanded to simulate the multidisciplinary characteristics of many iPEBBs, sources, and loads with control. A new DRTS system will be built.

The iPEBB demonstrator with the newly developed iPEBB control will be HIL tested in the new DRTS to qualify downloaded apps and iPEBB behavior. At the start for the 3rd year, all results will be combined to develop an On-Board Digital Real-Time Controller, OB-DRTC, for PEPDS.

iPEBB Control

Everything known up to this point about iPEBB - how it works, what it can do, how it fits and functions in a PEPDS - will be combined to create the iPEBB control in DRTS. Methods for high level programming the DRTS will be investigated. Processes for creating Software Building Blocks will be investigated. Methods for programming Software Building Blocks into downloadable apps will be investigated.

The Navy iPEBB is planned to be symmetrical and reversible. An iPEBB can be inserted into PEPDS with one side up, then turned over so the other side is up and inserted into PEPDS with no changes in performance. An iPEBB can be put anywhere in the distribution system. An iPEBB can control any load or source. These principles are implemented throughout this plan to reduce possible repair errors, decrease time to repair, make PEPDS sailor safe, easy to maintain, and affordable. The goal is to not need any sailor training to maintain and replace Navy iPEBBs. iPEBB programming will have to be done after the iPEBB is inserted in the system, when it is known where it is in the distribution system, and what the source/load is that will be controlled. When completed, the OB-DRTC will program the Navy iPEBB inserted in PEPDS. This will be demonstrated in the 4MW System Testbed.

1 to 1 Correspondence Between the Model and iPEBB Behaviors

During the development of the DRTS architecture and iPEBB control, experiments will be performed to establish methods and algorithms to create a 1 to 1 correspondence between the model and iPEBB behaviors. Toward the end of the 3rd year, the results will be validated and verified in simulation and with HIL testing of iPEBB demonstrator. When certification of the code is complete, the results will go into the development of the OB-DRTC. The final version of the Navy iPEBB, as a universal converter, will be designed and built.

Control

The Control tasks are shown in fig. 5. Control in existing power systems is on the order of milliseconds to seconds. Over a thousand-fold increase in power system control fidelity, accuracy, and precision is proposed. Sub-microsecond control of all the shipboard power and energy requires new power system control architectures, concepts, methods, mathematics, and hardware.

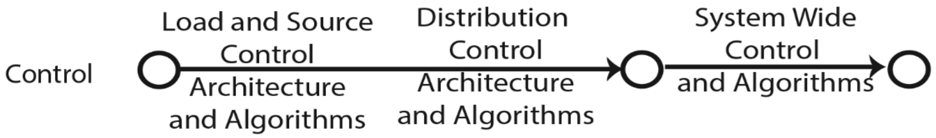


Figure 5. PEPDS Control Tasks

Control in the form of apps will be downloaded into Navy iPEBBs, like a laptop or smartphone. Unlike a laptop or smartphone, the Navy iPEBB handles power and energy as well as information. The Navy iPEBB is also like a robot, a Power Bot. Power Bots work together using swarm and/or other learning techniques to solve power system problems. Power Bots are capable of Deep Learning. Power Bots work together to perform distributed active filtering. Power Bots work together to perform distributed storage. Power Bots coordinate the energy of an entire system to fulfill every power need including pulse power. Power Bots work together to anticipate, identify, locate failures, and protect the system. Power Bots work together to maximize reliability and availability.

A Navy iPEBB will be universal, capable of performing any control loaded into it, rather than designed specifically for a single control application. Laptops and smartphones are not designed for only a few selected applications. They are designed to run as many apps as possible. They are designed to appeal to as many customers as possible, who have widely varying needs, to sell as many devices as they can. Ideally, PEPDS will be made of many iPEBBs that have the same hardware, with different programs for different applications. The traditional concept of converters will no longer exist. Instead there will be a cluster of iPEBBs with interaction specified by algorithms. The orchestrated interactions within the cluster result in converter functions.

Load and Source Control Architecture and Algorithms

More specifically, Navy iPEBBs will be capable of performing the following (and much more yet to be invented):

- Convert DC to DC, DC to AC, AC to DC, AC to AC from any source to any load
- Motor control

- Battery charging/regulation
- Pulse shaping/conditioning
- Actuator control
- Breaker
- Frequency Changing
- Radar Power Supply
- Generator Rectifier
- Electrical isolation
- Current limiting
- Fault clearing
- Health monitoring
- Sailor safe – replacement and repair
- Graceful Degradation

The PEBB control architecture for a single converter based PEBB is shown in Fig. 6. The proposed Navy iPEBB schematic shown in Fig. 7 has four converters. Research is needed to define the Navy iPEBB control architecture.

In Fig. 7, there are four converters, two on each side of the transformer. The Navy iPEBB is symmetrical, both sides are the same. As stated before, symmetry is important for achieving program goals. As stated before, it is intended that the iPEBB can be inserted in the system in either orientation. It is also important to reduce the number of manufacturing steps needed to produce the iPEBB.

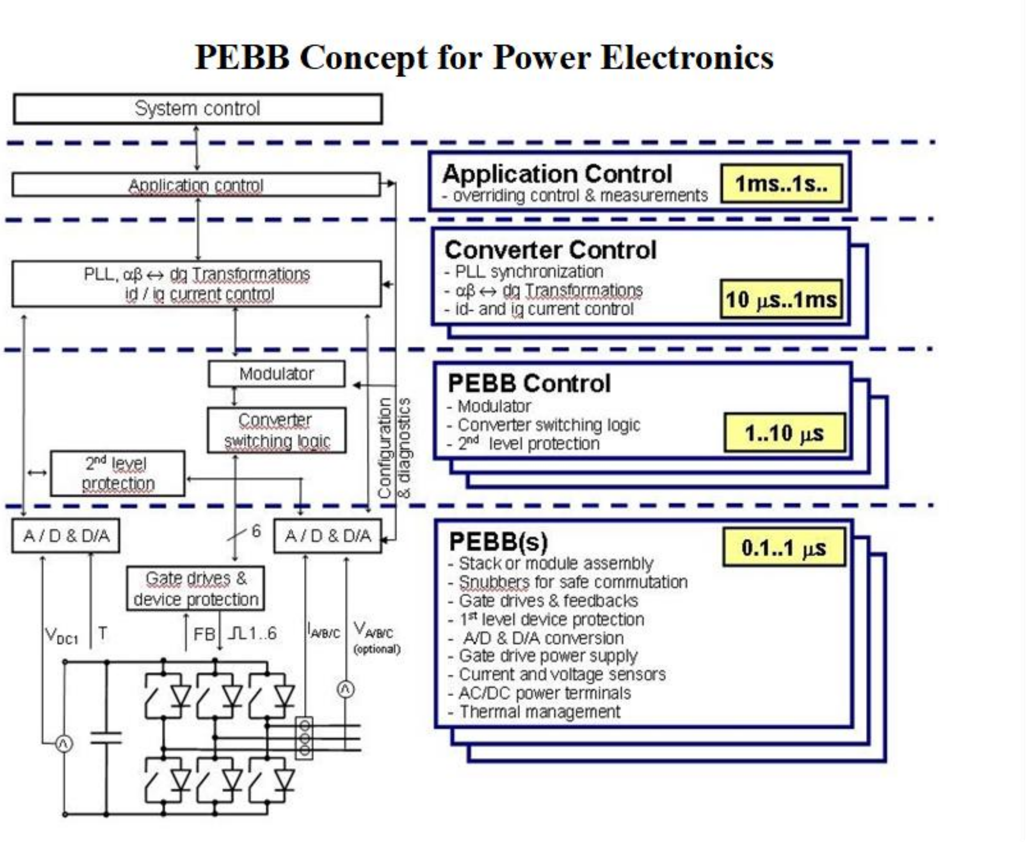


Figure 6. PEBB Control Architecture for a Single Converter PEBB

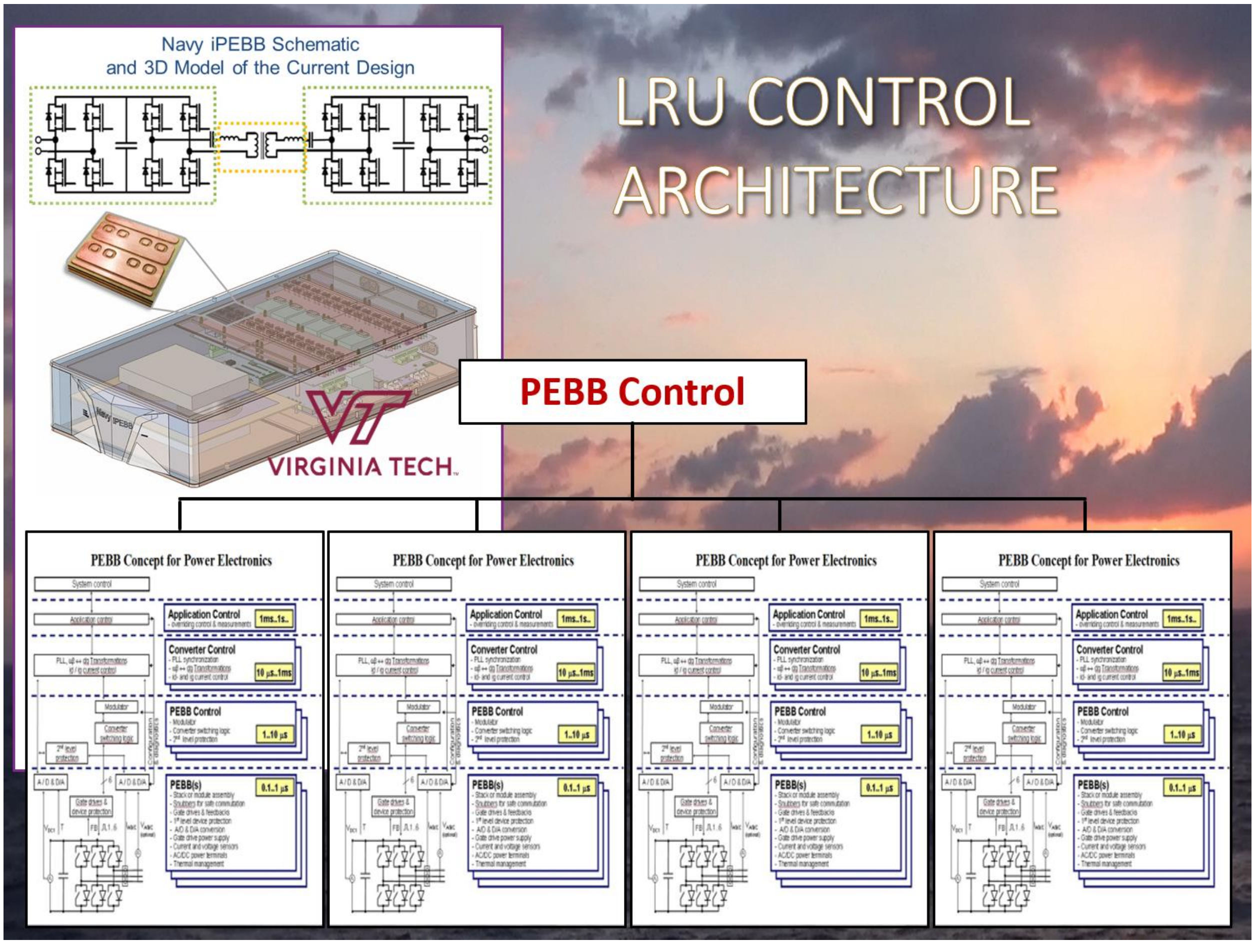


Figure 7. Navy iPEBB with 4 Converters

Distribution Control Architecture and Algorithms

Distribution control is a rapidly evolving concept. Whereas in MVDC and MVAC systems there is little need for distribution control, as it primarily employs breakers and switch gear for fault clearing, bus transfer, and such, PEPDS will have the Navy iPEBB to carry out power flow control and energy management with average control time frames in the microseconds range, and instantaneous control times in nanoseconds. PEPDS distribution control will have the following functions (and much more yet to be invented):

- Protection
- Power and current limiting
- Bus transfer
- Active Filtering (distributed and point)
- Energy Storage (distributed and point)
- Energy management
- Impedance control
- Graceful Degradation
- Reconfiguration

In Fig. 6, there is no control architecture above the dotted line. It has been proposed that the application layer is the lowest level of system control. It is also expected that the OB-DRTC is the highest level of system control. Investigations are needed to fill in the layers of control and establish the PEPDS system control architecture..

System Wide Control and Algorithms

System wide control is a new technical area because control in PEPDS includes detailed, comprehensive, and fast control of all the loads and sources in a ship. Every motor, generator, actuator, power supply, everything that gets or gives electrons to or from the ship power system is under control. After creating a system control architecture, a concept for System Wide Control will be developed. Every Navy iPEBB will be connected directly or indirectly to a common DC bus. Algorithms will be developed to control the interaction of all these iPEBBs to create multiple distribution functions, in accordance with the multifunction capability of the iPEBB. Investigations are hence needed to create the algorithms to control all the Navy iPEBBs within PEPDS seeking to apply the right function, at the right time, in the right place, while maintaining system stability and power quality. This is a new challenging research area that will determine and control both the power flow and energy management strategy onboard ships.

System Simulation

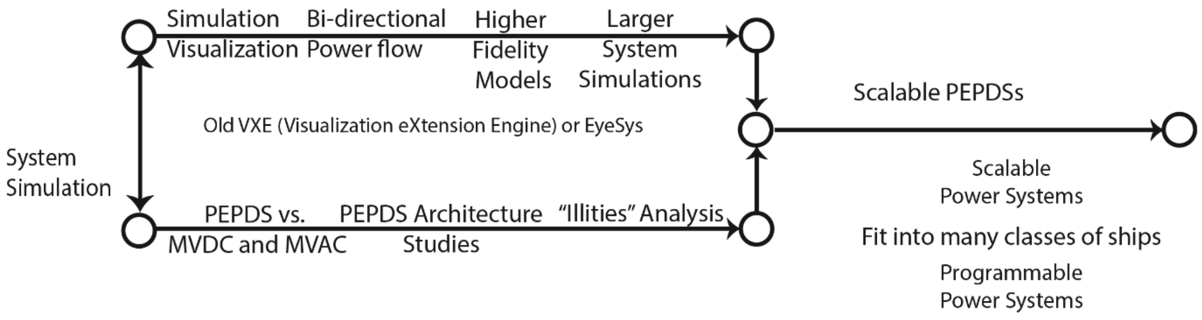


Figure 8. System Simulation Tasks.

The system simulation challenge is to simulate ever larger systems with more models and greater fidelity. The System Simulation Tasks are shown in Fig. 8. A new power system concept PEPDS will be developed from the bottom up in four concurrent science and technology layers. It will take about three years before we really know what a PEPDS is and the requirements for its simulation. Once we know what a PEPDS is, it will take about three years to develop the system simulation capability needed to simulate PEPDS. System simulation of PEPDS will require new models, concepts, and analysis methods.

However, system simulations are also needed to evaluate the development progress. System simulations are needed to compare PEPDS to MVDC and MVAC and to investigate the new system architectures possible from the technologies developed. It will not be optimum to wait until PEPDS development is complete to start the simulation system development. Consequently, system simulation development will begin concurrently with the other S&T investigations. As technologies and system simulation capabilities are developed, studies will be performed, and the results will be used to guide further developments.

A new system simulation environment will be developed starting with the ongoing ONR S3D program. S3D is a first of a kind thermal, electrical, mechanical, and hull simulation environment. Since PEPDS is a power electronic controlled power system, a sophisticated control simulation system capability will be developed for S3D. With some key developments (such as: visualization, power flow and control) S3D will be useful to begin with, although many more developments will be needed to meet the requirements of PEPDS.

Over the first two years, everything we know about system simulation will be investigated. Results from small and large modeling tasks, mechanical and thermal modeling tasks, control tasks, and model partitioning will be studied. The knowledge will be used to develop system simulation models and architecture. System simulation does not have to have a 1-to-1 relationship with iPEBB behavior that DRTS simulators must have. However, there must be a clear and precisely defined process relating system simulations to DRTS and ultimately with iPEBB behavior. System simulations must be translatable to and from DRTS. Standards, tools, and methods for developing these models will be established.

Simulation Visualization

Simulation visualization is key to performing concurrent engineering that incorporates several multidiscipline S&T developments. Everyone cannot know everything before anyone does anything. Visualization enables investigators to convey ideas and results to other investigators from different disciplines. “A picture is worth a thousand words.” Simulation visualization is worth a thousand pictures.

Visualization was a key part of ONR’s program 20 years ago. The Visualization eXtension Engine (VXE) and EyeSys were developed early on in ONR’s PEBB program. Over the years, these programs were left behind. The first thing to be done is to resurrect these programs and bring them up to current standards. Development can then begin to create the visualization engine needed for the PEPDS challenge.

Bidirectional Power Flow

Today system simulators assume power is flowing from the sources to the loads. In PEPDS systems, power flows in multiple directions. System simulators will be developed for iPEBB that can control power in and out, bidirectionally, on both the distribution side and the load and source sides. The system simulator will also be capable of simulating the management of energy across the iPEBB, from distribution side to load/source side bi-directionally.

PEPDS vs. MVDC and MVAC

A comprehensive investigation of PEPDS, MVDC, and MVAC is needed. Since existing tools for investigating PEPDS are yet to be developed, assessing PEPDS benefits over MVDC or MVAC is today more antidotal. New tools are needed. During the first and second years, new tools are to be developed in parallel with architecture studies -- starting with a study of PEPDS vs. MVDC and MVAC. These studies are intended to clarify differences between the architectures and define the limits of existing system simulation tools.

In MVAC systems, there is active and reactive power as generators produce AC power. In the case of existing shipboard systems, generators produce three phase AC and three phase AC is distributed throughout the ship. DC loads need converters to rectify AC to DC. In MVDC systems there is only active power flow. AC generators are still envisioned for these shipboard systems. Rectifiers convert AC to DC which is distributed throughout the ship and AC loads need controllers to convert DC to AC. Future MVDC systems may have DC sources and DC distributed to loads. Converters would be needed to convert DC to AC for AC loads. In addition, in a PEPDS system, every source can also be a load and every load can also be a source. Power from loads can and will flow to sources and be distributed to other loads.

Over the first two years, these architectures will be studied to refine the underlying concepts. System simulations will be performed to identify simulation software deficiencies and to evolve the architecture concepts. Simulation software upgrades will be performed throughout the two years to resolve the deficiencies and evolve the system simulation environment toward that needed for PEPDS.

PEPDS Architecture Studies

PEPDS is new and unique. A vast number of PEPDS architectural variations are possible. The analyses of PEPDS vs. MVDC and MVAC will lead to increasingly more mature ideas of each. As tools emerge from the simulation software development, the studies of potential architectures must begin. At the very forefront is the study of PEPDS as an advanced MVDC or MVAC. In these cases, PEPDS has all the monitoring and control capability; but controls power flow more like conventional MVAC and MVDC systems. This five-year program is an extremely aggressive concurrent engineering program. Any number of technologies may be limited beyond what is possible in this five-year period. Studies of what an ideal PEPDS could be vs. what PEPDS can be, based on successful technology developments (as they emerge) in this program are key to establishing and managing goals. Similarly, the study of PEPDS-enabled power flow control schemes will be conducted, from conventional continuous power flow to quantized “energy packets” schemes maximizing the power conversion capability of PEPDS.

“illities” Analysis

The “illities” of systems are the classic ways of describing what the Navy desires. However, many of these desires are not very qualitative or quantitative. Others, like Reliability, maintainability, and availability, are well defined processes and with well-defined calculations. However, these calculations depend on component and environment data that in a lot of cases are lacking or incomplete.

Often, progress is counterintuitive. For example, we know that “part count” reliability analysis is not a good predictor of future performance of power equipment. It has been very useful as a tool to compare different power equipment for shipboard applications. In more recent studies, the “part count” has been much less useful. New power circuit design concepts often add components to reduce circuits stresses. There may be more parts; but the stresses on the parts are reduced which could lead to increased reliability. There are more parts in the design which could lead to decreased reliability. There is a tradeoff between more parts and increased reliability.

This is the PEPDS problem. PEPDS adds multifunctional converters everywhere in the system. They control and manage power and energy stresses to enable increased reliability and performance. Adding converters everywhere adds more parts and cost to the system. PEPDS also employs LRU/MCD concepts to decrease Mean Time to Repair to increase reliability, availability, and reduce costs. Studies will be performed to understand these tradeoffs and benefits as a result of the technologies developed and the architectural variation discovered. PEPDS will also inherently enable the use of N+1 redundant schemes to further increase reliability, maintainability and availability.

As simulation capabilities increase, more capable studies will be performed to define, qualify, and quantify “illities”. Studies will be performed to define and characterize robustness, resilience, adaptability, affordability, and other “illities”. Studies will continue throughout the first 2 ½ years as new simulation capabilities emerge.

Higher Fidelity Models

Although there is no need for a 1-to-1 relationship between system simulation models and PEPDS component behavior, system simulation models must have increased accuracy. Increasing faithfulness of models to the components they represent is needed to enable system simulations to be useful for study of 2nd to 3rd order relationships of electrical, thermal, and mechanical properties.

Larger System Simulations

In addition to increased fidelity, system simulations need to include more models (thermal, mechanical, electrical, and hull); system control; power and energy management; thermal management; mechanical loads, and propulsion. This task will investigate the limits of system simulations considering the fidelity of models, number of models, computing power, and simulation duration. Standards, tools, and methods for system simulations will be developed for various computational platforms to assure repeatable results from studies performed by shipyards, Navy labs, and universities. Tools and methods will be developed to divide system simulations into sections for translation to DTRS for detailed studies.

Scalable PEPDSs

At the end of 2.5 years, all the system simulation tool improvements are combined to develop programmable power systems and scalable PEPDSs to fit any existing or future ship. At this point, the Navy iPEBB demonstrator will be complete and DRTS testing is underway. Control architecture, hierarchy, and partitioning will be completed. System simulations will be capable of evaluating PEPDS "illities" and architectural variations. The process for designing and developing PEPDS is finishing. The process from system design, to code development, to hardware implementation, and back again is completing.

The Navy has many classes of ships. Each ship will have varying missions. Also, each ship must have warfighting dominance over a lifetime that may be as much as 50 years. PEPDS must exceed the many contemporaneous needs as well as be ready for future demands. This task will develop tools and methods to enable scalability over the life of a ship as well as over all the classes of Navy ships.

With completion of the Higher Fidelity Models and Larger System Simulations tasks, tools and methods will be investigated to define scalability over computational platforms. Very large systems could be run on laptops. It may take a day, a week, or a month to run, depending on the size of the system and the computing capabilities of the laptop. Accordingly, the limits of system simulation on computing platforms such as laptops, pads, desktops, main frames, etc., will be studied. Standards, guidelines, and tools will be developed to scale system simulations and to measure confidence in computational results for specific computing platforms.

Real-Time On-Board Digital Control of Power System

The On-Board Digital Real Time Controller, OB-DRTC, controls the ship power and is the highest level of control in PEPDS. Just as there will be a one-to-one relationship between the DRTS model and the Navy iPEBB, there will be a one-to-one relationship between the DRTS models and OB-DRTC. System simulations produce a system design of interest. DTRS is used to study sections of PEPDS in detail to produce executable apps for the Navy iPEBB and other components. This task will investigate methods to port control from these sections to the ship to form a complete OB-DRTC for PEPDS. Methods will also be investigated to upload the OB-DRTC into DRTS sections that can be studied, modified, and reloaded into the OB-DRTC and transferred upward to system simulations.

Assuming the OB-DTRC will be the onboard programmer as well as controller, methods and tools will be developed to enable the OB-DTRC to download apps into the Navy iPEBBs, and all other ship components.

Methods and tools will also be developed to enable the OB-DTRC to receive health monitoring, learning changes, state information, and apps from Navy iPEBBs and all the components in the ship. The OB-DRTC will also assure sailor safety and ship security, identifying system issues and remedies. To this end, OB-DRTC will provide remedy instructions to the ship crew, guaranteeing that remedies will be safely implemented.

The results of scalability studies will be used to develop methods and tools for onboard computing assets (laptops, desktops, pads, main frames, etc.) to perform analyses of future events, contingencies, and restoration strategies. In addition, OB-DRTC will interface with shipboard computing assets to convey status, maintenance, and repair information to the crew.

Cyber Security and System Availability

Assuming all information to PEPDS and from PEPDS goes through the OB-DRTC, then OB-DRTC is the first place onboard that code can be examined before implementation in hardware. OB-DRTC is the last place changes can be interrogated for the potential of immediate harm and before transmission to off-ship studies. OB-DRTC is one of the key places in the PEPDS process to implement cyber security. Methods and tools will be investigated for onboard analysis and detection of harmful code and events. Learning methods will be investigated to ferret out hidden code and program errors.

iPEBB Universal Converter

During the third year, the Navy iPEBB Universal Converter will be designed, built, and tested. DRTS tests will be conducted to finalize apps, monitoring, learning, and cyber security. 1-to-1 correspondence between DTRS and iPEBB behavior will be certified.

iPEBB to System Control Hierarchy

The OB-DRTC is the highest level of system control. Once hardware and software can be finalized, the control hierarchy will be established. Control layers from the highest OB-DRTC control layer to the lowest iPEBB control layer will be defined. The control hierarchy developed will be studied to create scalable architectures and hierarchies for scalable PEPDSs.

Megawatt Scale System Testbed

Tools and methods from scalable PEPDS tasks will be used to design the megawatt scale testbed. System simulations of the testbed will be conducted to produce several different test scenarios. DRTS simulations for each of these sections will be developed.

An OB-DRTC for the testbed will be generated. Multiple Navy iPEBBs will be built, DRTS tested, and installed into the test bed. The 4MW testbed will be programmed. Apps will be downloaded into the iPEBBS and other components. Tests will be performed to verify and validate all the task developments.

Verification & Validation

Rigorous verification and validation (V&V) of models will be conducted throughout the program as the program will follow the new digital engineering paradigm. Therefore, during the last year of the program, the 4 MW testbed will be used to validate the full system models and to confirm and demonstrate the “illites” and PEPDS performance characteristics. System simulations of different ships under different missions will be performed. Digital Real Time Simulations and On-Board Real-Time Controllers will be created. The 4 MW testbed will be programmed to study these scenarios. At a minimum, the following “illites” will be demonstrated:

- Pulse Power & Power Dense
- Efficient
- Highly reliable & Maintainable
- Available
- Resilient
- Robust
- Adaptable
- Simplified Logistics
- Reduced Training
- Reduced Manning
- Affordable

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