Virtual Prototyping Process: Enabling Shipboard Sizing and Arrangement of a Power Electronics Power Distribution System

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***Abstract*—Naval shipboard power systems are complex and difficult to size and arrange due to their geographically distributed components. A modular Power Electronic Distribution System (PEPDS) built inside a Naval Integrated Power Electronic Corridor (NiPEC) has been proposed as a means of providing flexibility of power and energy delivery between sources and loads that significantly reduces electrical-thermal-structural overhead. In this study, a virtual prototyping process /that applies to PEPDS power trains is demonstrated. This approach enables the incorporation of digital twins of system building blocks, such as Power Electronic Building Block (PEBBs) and Integrated PEBB (iPEBBs) that have previously been reported on. The VPP ensures Pareto optimal integration of PEBB/iPEBB into PEPDS power trains and utilizes a unique dimensional compilation approach to account for the impacts of insulation coordination, repairability and thermal management on power density. This paper demonstrates Measure of Performance (MOP) outcomes of VPP and data management that can enable model based early-stage design exploration at the total ship level.**

***Index Terms*—MMC,VPP,PEBBS,S3D**

I. INTRODUCTION

A complex topic, shipboard power systems consist of various interconnected components such as generators, cables, switchboards, circuit-breakers, bus transfer switches, and loads throughout the ship [1]. This geographical distribution of the components makes shipboard power systems challenging to size and arrange. Adopting a Medium Voltage dc (MVdc) Integrated Power and Energy System (IPES) in future Navy ships has proposed as a means towards dynamic power/energy delivery to electrical Pulsed Power Loads (PPLs), Mission Loads (MLs) and Ship Service Loads (SSLs) that exceed installed generation capacity [2], IPES also promises increased fuel efficiency and enhanced mission capability through integrated electric propulsion [3] and has a distributed into aligned physical and electrical zones to increase survivability. interconnections are simplified, regenerative energy can be captured and utilized efficiently, and stored energy can be distributed without limitations. Recently, Medium Voltage dc (MVdc) Integrated Power and Energy Systems (IPES) for naval shipboard electrical distribution have been proposed as a means for enabling advanced weapon systems and, potentially, At the same time, Department of Defense (DoD) stakeholders are demanding ways to enhance Navy fleet capacity through accelerated timelines and enhancing mission capacity while simultaneously reducing ship sizes [4].

The IPES initiative requires the insertion of power electronic conversion between all sources of power and loads. Conventional approaches would attempt to implement IPES

This work is supported by the Office of Naval Research Grant No. N00014-20-1-2667,N00014-16-1-2956, and N00014-21-1-2124, and by the National Oceanic and Atmospheric Administration (NOAA) Grant No. NA22OAR4170126.

978-1-6654-6515-1/23/$31.00 ©2023 IEEE

through installation of procured groups of cabinets having specific power conversion functionalities, such as Medium Voltage ac (MVac) to MVdc active rectification and MVdc to Low Voltage dc (LVdc) transformer isolated conversion, non-isolated LVdc and Low Voltage ac (LVac) to Ship Service Distribution System (SSDS) power for MMLs and SSLs, etc. All of this implies the installation of extra power conversion equipment, on top of MVac switchgear and LVac/LVdc Ship Service Distribution System (SSDS) load centers and power panels. Such an approach will not achieve IPES without penalty to ship size and/or ship hull displacement unless some efficiencies are realized to reduce all of the associated aggregates of electrical-thermal-structural overhead [5].

To address the above challenges, the concept of a modular, building block-based Power Electronic Power Distribution System (PEPDS), constructed within a Navy integrated Power and Energy Corridor (NiPEC), integral to ship hull/bulkhead construction, has been proposed. The NiPEC-based PEPDS is building block based and relies upon the Office of Naval Research (ONR) Science and Technology (S & T) investments in PEBB and iPEBB development. PEBB/iPEBB are multi-use building blocks that can be configured in series, parallel and cascaded arrangements to realize a wide range of power conversion functions, i.e. MVac-MVdc, MVdc-LVdc, etc. in various forms or topologies. Because the IPES achieves its flexibility in routing of power/energy through common inter-zonal MVdc and (potentially) LVdc buses, connected longitudinally througout the ship. conversion of power between points of source and load will necessarily involve two or more power conversion stages. A cascaded connection of power stages between points of source and points of load (or feed) are referred to in this paper as a power train, or *PEPDS power train* [6]. For design space exploration a PEPDS power train is represented by cuboid physical dimensions and mass, and electro-thermal performance, including switches for re-routing, electrical-thermal-structural interfaces that comprise the configuration of PEBBs/iPEBBs required to realize required source input to load output functionality of that power train, Any physical section of NiPEC in the ship will consist of multiple power trains as is illustrated notionally in Fig. 1

The NiPEC/PEPDS itself is a very complex system and its feasibility within a total ship system is difficult to assess in terms of the Technical Performance Measures (TPMs) that shipbuilders care about, such as total NiPEC physical space claim and hull displacement. However, there are Measurements of Performance (MOPs) that are meaningful when comparing a multitude of possible configurations of PEBB/iPEBB building blocks to realize power/energy delivery through multiple power train paths between power/energy source and loads throughout the ship. These MOPs, assessed for each power train inlude power density (ρ), specific power (γ), specific cost (σ) and efficiency (η).

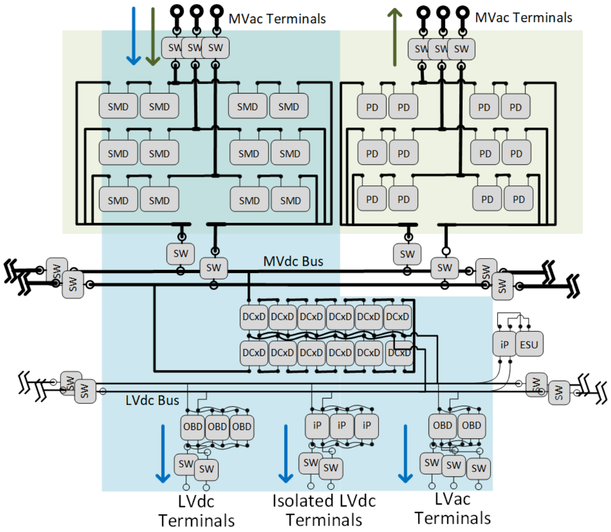


Fig. 1: Notional PEPDS Power trains

The purpose of this paper is to describe and provide preliminary demonstration of a Virtual Prototyping Process (VPP) for NiPEC-based PEPDS power trains that will result in a meaningful methodology for solution space exploration that utilizes resultant MOPs of distinct power trains. The VPP is essential to the production of MOPs against which various realizations of PEPDS can be assessed. VPP also produces, as an outcome, scalable metamodels [7] for the electro-thermal-physical representations of multiple power trains to enable Set-Based Design (SBD) of the ship system in a Rapid Ship Design Environment (RSDE). The ultimate goal is to be able to correlate MOPs of individual power train solutions to the ship-level TPMs so that, eventually, equipment can be successfully procured to realize NiPEC/PEPDS in future ship design activities. This work is part of a multi-university initiative for PEPDS integration that will utilize the MOPs produced to inform a Model Based Systems Engineering (MBSE) that drives PEPDS requirements based upon Measures of Effectiveness (MOEs) derived from stakeholder needs [8].

II. BACKGROUND

A. PEBB/iPEBB

Scalability and configurablity of PEPDS is realized through the use of PEBB/iPEBB. The PEBB6000 has demonstrated the use of PEBB as convenient means for new technology insertion into building block systems. PEBB6000, utilizes 10kV rated Silicon Carbide (SiC) MOSFETsof PEPDS in an H-bridge configuration and can realize modular topologies for medium voltage power conversion, such as the Full-Bridge Modular Multilevel Converter (FB-MMC), which can very effectively integrate the current limiting functionality required by breakerless protection schemes with MVac-MVdc power conversion functionality. Recent work on a power cell design and assessment methodology for the 10kV SiC MOSFET based half-bridge mirrors the VPP for a single point design that has led to a validated hardware design at a relatively high Technical Readiness Level (TRL) [9], (i.e. TRL-4). The most current generation of the PEBB6000 corresponds is built upon this previous work and the design around that building block can proceed through an informed application of [9] as a datasheet. The PEBB6000 then becomes the core building block used by the VPP for the MVac-MVdc stage of both power trains and the MVac-MVac power train of Fig. 1.

The MVdc-LVdc, MVdc to isolated LVdc (MVdc-iLVdc) and MVdc-LVac power stages of the MVac to Low Voltage Distribution System (MVac-LVDS) power train of Fig. 1 require the use of outcomes of ONR S & T investment in the iPEBB and its variants. Development of iPEBB,a 1 kV, 250 kW, 500 kHz building block [10], is motivated by a drive to increase PEPDS survivability, flexibility and controllability by allocating higher levels of functionality to the building block. The iPEBB vision seeks to push the power, frequency, weight ($<$ 35 lbs), and power density (approximately 12 kW/l) aspect of PEBBs through high-density integration and converter-level packaging. The converter houses four H-bridges, a high-frequency transformer, dc-link capacitors, and circuitry. The iPEBB resonant topology is realized by bonding and interconnecting 1.7 kV SiC MOSFET bare dies and passive components to a common substrate. The common substrate will provide multiple functions, including electrical connections through a substrate-based busbar, a unified cooling interface, and mechanical support for the entire converter [11]. Each common substrate (on either side of the converter) has two H-bridges to form the primary and secondary sides of the converter. An advantage of the H-bridge submodule is that it's an inherent part of the common substrate and does not require additional baseplates or interface layers to connect with the rest of the converter. Hence, the H-bridge sub-module utilizes multi-layer organic direct bonded copper (ODBC)-based common substrate to maximize power density and manufacturability [10].

In the current design iteration, each H-bridge sub-module has six 1.7 kV SiC MOSFETs in parallel to meet the current ratings and is housed on a 15 cm x 10 cm layout. The multi-layer design is part of the H-bridges commutation path and enables reduced power loop inductance and better current sharing between parallel MOSFETs [12]. Additionally, external antiparallel diodes are eliminated using the superior reverse conduction characteristics of the MOSFET body diode. This enables fewer discrete devices on the substrate and simplifies the manufacturing process. Furthermore, the H-bridge design is symmetric and can be paralleled to achieve higher current and can be used for the inner soft-switching H-bridges and the outer hard-switching H-bridges of the iPEBB. As the iPEBB and its variants progress through TRLs, the NiPEC-PEPDS design exploration can proceed as performance data derived from hardware prototypes becomes available.

B. *VPP*

The use of virtual prototyping, in general, enables explore a wide range of design decisions, through methodological design space exploration, in a virtual, multi-disciplinary environment. In fact, a virtual prototyping process resulting in iterative hardware prototypes, validating this the design process and efforts, is followed in [9]. The combination of virtual prototyping with multi-objective optimization has been introduced and applied to power electronic conversion system analysis to (1.) assess increases in power density, efficiency, and specific cost (power per cost) that can be achieved with new topologies, modulation schemes, and WBG power semiconductors [8]; (2.) concurrently optimize within thermo-electrical, thermo-mechanical and electromagnetic design domains; and (3.) assess the merit of one topology versus another [13].

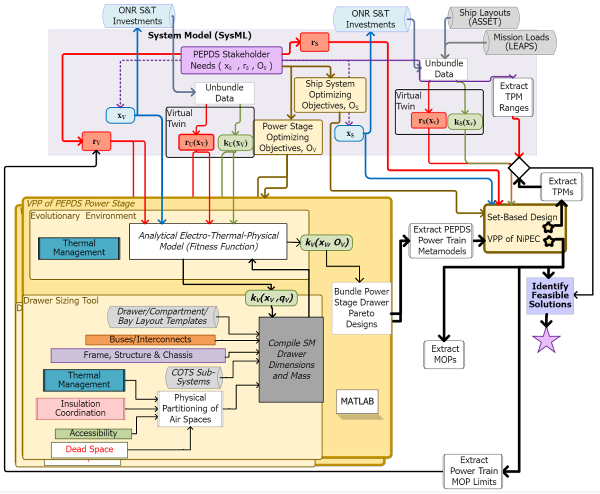


Fig. 2: Virtual Prototyping Process

The authors have developed a unique VPP, suitable for building block based power conversion systems [14], [15], represented in Fig. 2. The VPP allows for exploration of a range of design space variables that impact a PEPDS power train, $\mathbf{x_V}$. These are sub-sets of ship level variables, $\mathbf{x_S}$, used for integration of NiPEC into the ship structure and follow-on SBD using a total ship model. The PEPDS power train design space variables to the VPP include MVdc bus voltage level, V_{DC}, ambient temperature of air or water, T_A used to extract heat from PEBB/iPEBB heatsinks, PEBB/iPEBB type, and power converter topology. To achieve the inclusion of PEBB/iPEBB in the design exploration space, the VPP must relies upon virtual twins of PEBB/PEBB that can be traceable, through parameters and identifiers used within the VPP, to the current physical prototype data extracted from PEBB/iPEBB development efforts. Various forms of PEBB/iPEBB virtual twin are used, in the form models using appropriate parameters, $\mathbf{k_U}(\mathbf{x_V})$, and constraints, $\mathbf{r_U}(\mathbf{x_V})$ extracted from PEBB/iPEBB physical representations.

The VPP also incorporates practical considerations needed to produce realistic designs. For example, the PEBB/iPEBB building block functional insulation capability may not match the line-to-ground voltage stresses applied at the ship level and, as a result, associated PEBB/iPEBB heatsinks and ship level thermal connections would necessitate isolation of the PEBB/iPEBB (and thermal interfaces) by ensuring clearances from the NiPEC chassis. This can be accomplished, without sacrificing plug-and-play maintainability by incorporating PEBBs/iPEBBs into drawers that enforce necessary creepage and clearance distances, derived from an insulation coordination process. Furthermore, the PEBB or iPEBB may not be able to implement the full functionality of a power conversion stage topology without additional passive elements, as Line Replaceable Units (LRUs) to augment internal dc-link capacitance or provide filtering. To account for all of these practicalities, the PEBB/iPEBB and passive LRUs are organized into Sub-Module Drawers, which become the power train building block.

Referring to Fig. 1 the revised power train building blocks are: (1.) PEBB Drawer (PD) for the PEBB6000, including space allocations for thermal management and insulation standoff (clearance) that accounts for the difference between functional insulation capability of the PEBB6000 and basic insulation requirement of the MVac or MVdc voltage level derived from an insulation coordination process [16]. The MMC MVdc-MVac converter with PDs assumes the application of Switching Cycle Control (SCC) to minimize the need for external passives beyond what is inherently within the PEBB6000 [17]–[19]; (2.) The isolated dc-dc part of the iPEBB (DCx) incorporated into a Drawer (DCxD) with space/mass allocations for thermal management, bus interconnections and insulation standoff (clearance) that accounts for the difference between functional insulation capability of the iPEBB and basic insulation requirement of the MVac or MVdc voltage level [16]; (3.) Sub-Module Drawer (SMD) of a PEBB6000 plus arm inductance distributed to sub-modules and additional sub-module capacitance with conventional FB-MMC controls with MVdc-side current arresting capability [20], [21], plus allocations for thermal management and dielectric clearances (see Fig. 6). (4.) The iPEBB (iP) for loads connected to the iLVdc terminals; and (5.) variants on the Outer Bridge (OB) parts of the iPEBB, which are 1kV rated H-bridge modules configured into drawers with appropriate passive filtering (OBD) for interfaces to loads at LVdc and LVac terminals.

The purpose of VPP is to generate sets of designs for power trains corresponding to all combinations of design space variables in $\mathbf{x_V}$ that have been optimized ρ-γ-σ-η in an evolutionary optimization environment. The ρ-γ-σ-η objectives represent a sub-set of MOPs derived from the MOEs of stakeholder needs through a System Model that manages all system functional requirements. The analytical electro-thermal-physical model searches for solutions in the evolutionary environment over the design space and optimizes the passive LRUs, according to pre-set templates of arrangements with corresponding PEBB(s) or iPEBB(s) in a SMD, PD, DCxD or OBD. Parameters, constraints and appropriate performance models are extracted solution sets that lie on Pareto surfaces, so that metamodels of the power trains can be reconstructed in a total ship Concurrent Engineering (CE) environment for a continuation of a similar VPP of the NiPEC that accounts for all possible power train solutions sets that will be made available through metamodel extraction and data storage of each possibility. In this way, all of the electro-thermal-physical characteristics of NiPEC-based VPP can be incorporated into ship level SBD to identify the feasible solutions that meet ship level TPMs. It should be noted that iterative executions of the VPP on all possible PEPDS power trains are necessary to inform that goal and objective levels of the MOPs that will ultimately be imposed on the NiPEC-based PEPDS by the System Model.

C. Thermal Analysis

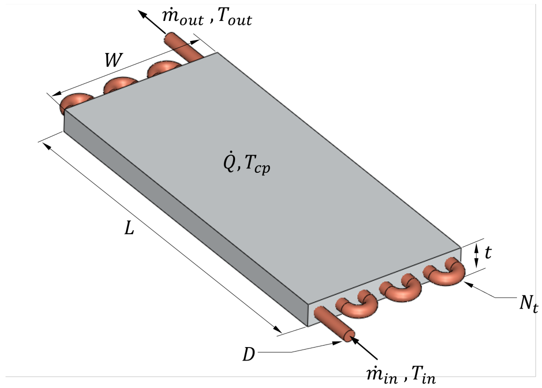
For thermal management, the VPP requires the creation of a virtual twin of the physical twin of thermal management components, such as heatsinks, fans, coldplates and heat exchangers. The dimensional and mass attributes of these components populate the thermal allocations during the Drawer Compilation sub-process of VPP. This aspect of VPP is critical because the thermal support capability of the ship system upstream must dictate the power throughput ratings of the power trains, rather than assigning power ratings to blocks based upon point design exercises at under a single set of environmental conditions. The thermal mangement components are the means whereby the inlet water temperature and mass flow rate, provided by the ship-level thermal management system, translates into intrinsic power capacity (or installed power capability) of the power train.

Applying this concept to thermal management of PEBB(s), iPEBB(s), passive LRUs etc. comprising a power train, a virtual twin of the thermal management system must be described in a computationally efficient way to serve VPP iterative processes leading to the determination and matching of the losses with the cooling capacity. This aspect of VPP is critical because, in order to ensure optimal power train solutions over a design space that includes connections with thermal management at the system level, the intrinsic power capability of a power train, P_{oi} must depend upon the ambient temperature, T_A and mass flow rate $\dot{q}$ of the supplied air or water for heat extraction

In this study, a liquid coolant is used to thermally manage heat-dissipating components using forced convection as the primary heat transfer mechanism. At the PEBB level, cold plates are employed. Fig. 3 illustrates the essential elements of the cold plate geometry. For inductors, cold plates are arranged and interconnected to cover the four lateral sides, forming a cooling jacket.

At the cabinet level, the coolant mass flow rate seen by a cold plate serving a PEBB is dictated by the pump, likely located at the bay level, and the cooling network configuration. For this reason, the coolant mass flow rate is treated as a design variable, whose value will result from the VPP process.

A cold plate sub-block within VPP relates the cold plate geometry (number of channels, channel geometry, internal features), the cold plate material (e.g., copper, aluminum), the coolant type, the coolant mass flow rate and the coolant inlet temperature with the pressure drop across the cold plate, the associated pumping power, the heat transfer rate and the temperature difference between the coolant inlet temperature and the cold plate surface. Adding thermal interface and device



$$(\Delta T, \Delta P) = fn(\dot{m}, T_{in}, D, N_t, t, W, L, \dot{Q})$$

Alternatively, $(\dot{Q}, \Delta P) = fn(\dot{m}, T_{in}, T_{cp}, D, N_t, t, W, L)$

Fig. 3: Schematic of cold plate geometry. The digital twin provides a functional relationship connecting geometrical features, operational conditions, and performance.

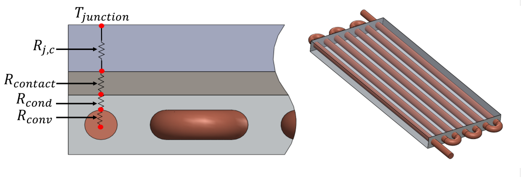


Fig. 4: Schematic of thermal resistances between coolant and module.

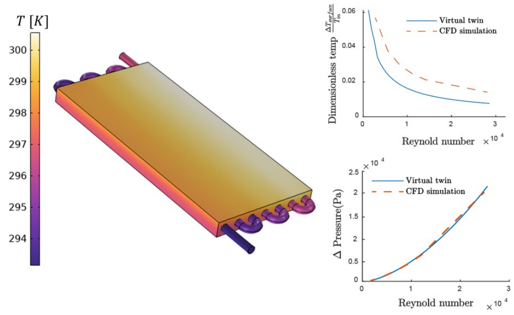


Fig. 5: Comparison of pressure drops and temperature gains obtained with the digital twin model against CFD.

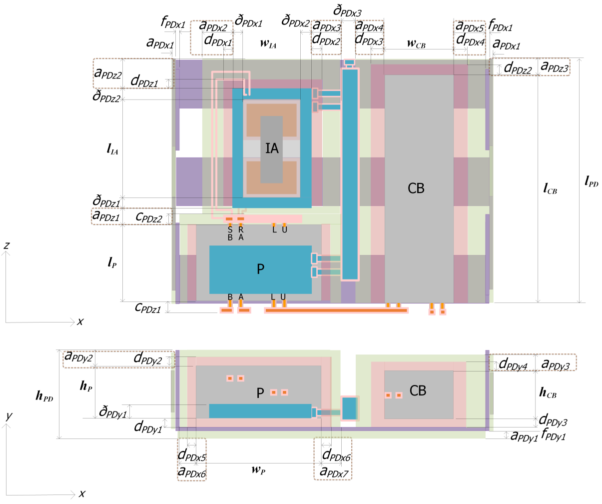


Fig. 6: PEBB 6000 based SMD (Layout 1)

resistances, the sub-block is extended to account for device (e.g., junction) temperatures 4.

The pressure drop across the heat sink is determined from the minor and major losses taking into consideration the flow regime to determine the friction coefficient. A thermal equivalent model was used to determine the Junction-to-coolant resistance by relying on Nusselt number correlations according to the flow regime. The Nusselt number correlations are used to determine the convective resistances.

As mentioned, the virtual prototype has to be expressed in a computationally efficient manner, that preserves the level of accuracy needed to make informed decisions at the VPP level. The cold plate module used was compared against CFD simulations. Figure 5 summarizes that comparison between pressure drop estimations and temperature difference estimations obtained from the digital twin and CFD simulations at different Reynolds numbers.

III. Power Train Development

As a use case, a power train is constructed for MVac to MVac points of source and load, where the MVac input comes from a generator and the MVac output is a variable frequency supply to a propulsion motor, described by the green boxed areas of the PEPDS power trains in Fig. 1—the use of PEBB6000 as the selected PEBB type is assumed. The goal of VPP is to find the intrinsic power throughput capability of the power train, which means operation at the highest output MVac voltage (and corresponding frequency), maintaining junction temperatures of PEBB power semiconductors and hot spot temperatures of the passive LRUs at maximum levels for the most limiting power stage of the power train. To achieve this end, MVac-MVdc conversion is achieved with a FB-MMC, comprised of SMD building blocks, and MVdc-MVac conversion with SCC control, comprised of PD building blocks. This assumes that the FB-MMC manages MVdc faults by arresting fault current responses through augmented capabilities of the SMD but that the MMC implementation of the MVdc-MVac can meet its performance requirements without the additional passive LRUs of the SMD. This approach assumes that control capability within the MVdc-MVac stage enables maximum use of the PEBB without external passives and that the surrounding capabilities of PEPDS power trains can adequately perform fault management. Also included in the power train are ac and ac-side electro-mechanical disconnects to provide galvanic isolation following fault event responses and during maintenance operations.

A. PEBB/iPEBB Sub-Module Drawers

The VPP, which simulates numerous elements and modifies the design as necessary to maximize performance, efficiency, and reliability, can be a potent tool for assessing the physical partitioning of a PEPDS system. Each PEBB is placed in the SMD and optimized to achieve the maximum possible intrinsic power, P_{oi}, as determined from T_A and $\dot{q}$ and power density, ρ, or efficiency, η over the performance space.

- Bus/Interconnections: The physical area is available for internal SMD wiring and blind-made plugs. Ensuring enough cable space for all necessary connections is essential to avoid congestion and potential shorts [22]. Taking this allocation to consider arrangement impacts that would go against safe procedures.
- Frame Structure: The frame structure is the actual physical framework that houses the power converter's component sections. Ensure the frame structure is strong enough to sustain the components' weight and forces while being lightweight and compact. The frame structure can be evaluated. The design was updated to obtain the optimal strength-to-weight ratio by simulating the forces and stresses applied to the structure in the VPP.
- Thermal Management System: To prevent overheating and damage to the power converter, a system of components and practices called thermal management regulates the power converter's temperature. The thermal management system must be easy, practical, efficient, and compact. By simulating the heat generated by the parts and the effectiveness of cooling techniques, the thermal management system in the VPP can be evaluated. The design can then be modified as necessary to maintain perfect temperature control.
- Insulation Coordination: The "insulation coordination" system of components and practices protects the power converter from thermal and electrical failure. Ensuring the insulation coordination system is lightweight, small, and efficient is essential. Insulation coordination may be evaluated by simulating the electrical and thermal pressures on the power converter in the VPP. The design can then be modified to provide the finest insulating protection feasible.
- Accessibility: Accessibility is the simplicity with which components can be removed for maintenance and repair. It's critical to make sure the power converter is built with accessibility in mind to reduce downtime and maintenance costs. By replicating the process of maintaining components and making the necessary design changes to permit the highest ease of maintenance, the accessibility of the VPP can be evaluated.
- Dead Space: The physical space not occupied by cables or components is called dead space. To make the power converter lighter and more efficient, dead space must be reduced. Dead space can be evaluated, and the design adjusted to decrease unneeded space by simulating the placement of items and wiring in the VPP.

TABLE I: Gene parameters for NSGA-ii

#	Min Val	Max Val	Description
1	6	18	Tcr (Type of core material)
2	1	1	Tcd (Type of conD.ind. material)
3	1e-4	0.1	g (gap, m)
4	0.1	10	lc (length of core, m)
5	1e-2	5	wc
6	0.4	2	rec
7	0.4	3	rie
8	0.4	3	rbe
9	1e-4	40	ac*
10	1	1e3	N*
11	1	0.7e3	Nw*
12	1	0.5e3	Nd*
13	1e-6	1e-1	cw
14	1e-6	1e-1	cd
15	1	435	caps selection
16	0.34e-3	0.09	cap Value (F)
17	1	3	Caps Oriantaion
18	1e6	50e6	intrensic power
19	1	50	cap length limit
20	1	2	levels of caps

1) NSGA-ii:

1) NSGA-ii: The multi-objective optimization technique NSGA-II is often used to find the Pareto optimal front for a set of objective functions. (Nondominated Sorting Genetic Algorithm II). A set of solutions known as the Pareto optimum front makes it impossible to improve any objective function without worsening at least one objective function. Power density, efficiency, cost, reliability, and other stakeholder criteria could be the PEPDS system's goal functions [23]. A population of initial solutions represented as decision variables are first created via NSGA-II. (e.g., converter topologies, power levels, control strategies, etc.). The algorithm then evaluates the performance of each solution concerning the goal functions, using Table. I Gene parameters for NSGA-ii The solutions are then ranked according to their non-domination level, which is determined by comparing their fitness values. The non-dominated solutions are then chosen for reproduction, which entails combining the decision variables of the chosen solutions via crossover and mutation to generate new solutions. After a given number of generations or until the Pareto optimal front is located, the new solutions are assessed and graded using the same technique. Table. I shows the genes employed in the NSGA 2 for this approach. VPP offers the speedy and effective evaluation of numerous alternative solutions due to its ability to run simulations concurrently and automatically rate the results. This enables designers to explore multiple design possibilities and trade-offs to establish the optimal PEPDS system solutions based on the stakeholders' requirements [24].

2) Insulation coordination: Coordination of insulation is critical for electrical system safety and reliability. It is necessary to ensure that the insulation utilized in the system can withstand the electrical stress is utilized in the system can withstand the electrical stress that it will be subjected to. This includes adhering to the dielectric stand-off, creepage distance, and clearance between conductive elements requirements of the IEC and IEEE standards [16]. These specifications must be followed by the PEBB, inductor, and capacitor bank to ensure

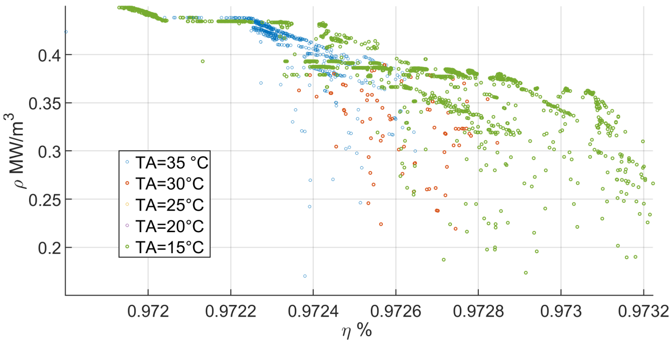


Fig. 7: MVac-MVac power train power density (ρ) vs. efficiency (η) Pareto solutions as a function of inlet water temperature, T_A for $V_{DC} = 12kV$

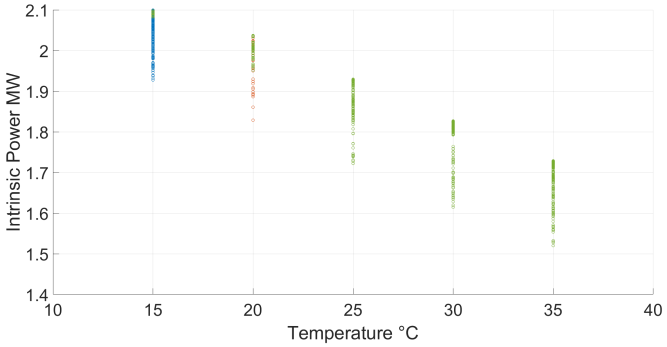


Fig. 8: Power train intrinsic power (or installed power capacity) vs. inlet water temperature for $V_{DC} = 12kV$

that the parts can withstand the rated voltage level while avoiding electrical breakdown and arcing. The MMC's insulation coordination specifications influence the size of the drawers, and the inductor and capacitor bank must be built with enough space between components to ensure safety. Adhering to the applicable standards allows for the proper design and sizing of the components, ensuring the safe and dependable operation of the entire PEBB system. The NSGA 2 algorithm can be used in the set-based design procedure to help select the best potential solutions from the available options. This process evaluates and ranks solutions using various criteria, making it a multi-objective optimization algorithm. The designer can use NSGA 2 to examine the performance of each prospective solution using a range of performance measures and obtain a list of optimal solutions. [16]

IV. Virtual Prototype Analysis

The efficiency and power density of a given power train are key MOPs from against which various solutions for the NiPEC-PEPDS. The power density (ρ) versus efficiency (η) Pareto solution outcomes of the VPP, as a function of the inlet water temperature (T_A) design space variable are shown in Fig. 7. These results represent the ratio of the intrinsic power capability (P_{oi}) of the power train enabled by varying levels of inlet water temperature made available to the SMDs and PDs to the total space claim of those drawers. The final MOPs must account for the space claim within NiPEC, including bussing and piping. The MMC solutions to these power trains represent a relatively high efficiency but power density that may be lower than expected, given the high power density of the PEBB 6000s themselves (20kW/l). However, this result shows the true value of expressing these important MOPs in this manner, at the power train level, where they are truly meaningful. The low power density is attributable in part to the MMC topology, added passives in the SMD and the dielectric clearances required to match the 6kV PEBBs with the higher system MVdc voltage of 12kV (as well as other considerations such as space for maintainability within a multi-LRU drawer). Nevertheless, the impacts of these practicalities must be captured in the measures of performance within the solution space. The VPP allows for an exploration of additional design space variables, such as MVdc bus voltage level, MVac frequency, PEBB type, thermal management approach and topology.

Figs. 8 shows the relationship between the installed power capacity of the power train (P_{oi}) versus inlet water temperature, T_A. The range of temperatures accounts for consideration of chilled water versus non-chilled water and upstream temperature rise associated with de-ionization of the inlet water (to allow for floating of the coldplates, which is essential to the ensuring reliability of the the insulation substrates of the power semiconductors in stacked topologies). As expected, the highest power throughput is achieved with lower inlet water temperature and the power capacity falls off with increases in T_A.

The findings of the study have implications for designing and improving MMC-based power trains for shipboard PEPDS applications. Clearly, the use of SCC control techniques (as applied to the MVdc-MVac power stage) will enable the usage of switching frequency as a design exploratio variable to increase power density for MMC-based solutions. This option is not available for the conventionally controlled FB-MMC topology implemented by the SMDs. Further work is required to incorporate control techniques as a design space variable within the VPP for this topology. Also, additional solutions can be explored utilizing iPEBB, and variations thereof, as the building block. Again, these results represent only a single power train from MVac to MVac source/load interfaces for a single PEBB building block. The MVac-LVDS power train will require studies with the iPEBB and iPEBB variants such as the DCx and OB. This work is currently being performed by the PEPDS integration team.

It is also important to note that the VPP is only one part of the solution space exploration for NiPEC-PEPDS solutions. The main purpose of VPP is produce building blocks for PEPDS that can be further explored by considering various arrangements within the NiPEC to maximize the MOPs. While this study produces only two MOPs for a single power train (with a limited set of design space variables) it demonstrates the range of the MOPs to be expected. The MOPs will reduce once the integration within NiPEC is considered, along with the impacts of other important parts of the power train, such as the isolating switches. Once sets of solutions representing a particular electrical framework (or architecture) are quantified and determined to be feasible within the ship space (i.e. according to TPMs) system level dynamic analysis of these solutions must be performed to assess other performance measures, such as survivability vs. operability, to further assess and down-select to the best solutions. Also, there are other MOPs that must be considered, such as specific cost, specific power and reliability.

V. SHIP SYSTEM APPLICATION

A sample PEBB-based PEPDS concept was applied to a notional all-electric destroyer-type warship to provide the framework for subsequent analysis. Anticipated electrical loads were reviewed, assessed, and accounted for to construct a nominal allocation and breakdown of the ship's power demand. These loads included major combat weapons systems (*e.g.* dual-band radars, sonar suite equipment, Vertical Launch System, laser, railgun), primary propulsion and engineering equipment (*e.g.* permanent magnet motors (PMMs), gas turbine generator sets, chillers), and various allowances for miscellaneous AC and DC loads.

[25] outlines the stakeholder needs, behaviors, structures, and measures for PEPDS in a system model. This paradigm guided the creation of the sample PEPDS concept. Some of the tenets employed include: power electronics form the interface between the distribution system and each power source or load and control the flow of power; independent, redundant sources of power are provided to each vital load; and the LRU concept is applied to the conversion process. Note that this is not proposed as an ideal solution; it is merely one possible solution that enables the exploration of different concepts. The assumptions made for this example system follow:

- AC power is generated and immediately converted to dc for distribution
- The main power distribution bus is set to 12kV medium voltage dc (MVdc)
- A secondary power distribution bus is set to 1kV low voltage dc (LVdc)
- Redundant power distribution buses are provided for robustness/survivability purposes
- Two LRUs are employed: the iPEBB at 250kW, 1kV internal bus voltage, and the PEBB6000 at 1000kW, 6kV internal bus voltage
- High-power loads (greater than 1MW) are fed from the MVdc bus via dedicated PEBB-6000 converters
- Low-power loads (1MW and less) are fed from the LVdc bus via iPEBB-based converters and may be grouped to share a converter
- Conversion is provided for each load within the watertight subdivision in which that load is located
- Energy storage at 1kVdc is tied to the LVdc bus

A portion of the resultant electrical one-line diagram, produced using S3D, is shown in Figure 9. This entire system was used to elucidate individual requirements for power conversion.

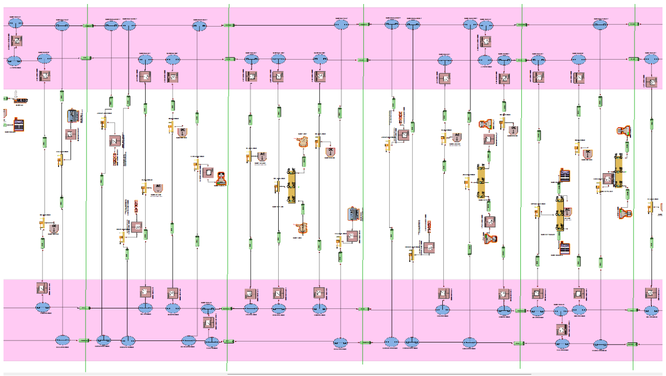


Fig. 9: Sample PEBB-based PEPDS power distribution system applied to the notional warship.

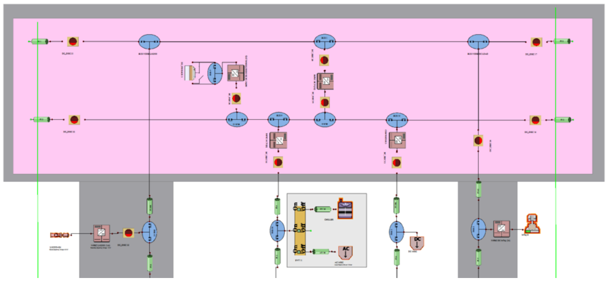


Fig. 10: Generic half-zone model displaying typical power train conversion requirements.

From this large system, several power trains were identified:

- Power generation, converted from three-phase ∼8 kVac to 12 kVdc
- High-power mission load power drawn from the MVdc bus, and power flowing from the MVdc bus to the LVdc bus, require conversion from 12kVdc to 1kVdc
- In-zone low-voltage dc loads draw power from the LVdc bus and require conversion from 1kVdc to a lower voltage; note that even if loads are at 1kVdc and do not require conversion, there will still be a PEBB interface to control the flow of power
- in-zone ac loads draw power from the LVdc bus and require conversion from 1kVdc to three-phase 450 Vac
- bus-tied energy conversion requires bi-directional control of power flow from the 1kVdc bus to and from a 1kVdc energy storage device

A generic half-zone was constructed in S3D to model these individual power trains, as shown in Figure 10.

De-ionized water is typically used for electronics system cooling in order to reduce corrosion and to reduce the opportunity for short-circuit should the water come into contact with the electronics. A sample de-ionized water system design for the NiPEC provides supply and return headers underneath the PEBB bays, with branch piping for each bay tapping off these headers at the side of the bay stack. Multiple heat exchangers along the length of the ship then transfer the heat from the de-ionized water system to the ship's chilled water system.

In the four-corridor arrangement shown in Figure 11, PEBBs are arrayed in PEBB bays within each watertight subdivision (indicated by vertical lines). The PEBB bays are placed atop a base that contains de-ionized water supply and return headers. Six heat exchangers, three to port and three to starboard, are arrayed along the length of the ship and are connected to the headings within the NiPEC via risers.

A single power train representing the conversion of 3MW of generated MVac power to distributed MVdc power in an MMC converter arrangement consists of 12 PEBB-6000 drawers. To take this to an in-zone load at 1kVdc or 450Vac requires an additional 12 iPEBB drawers. Figure 12 shows a full 3MW MVac to LVdc power train arranged within a NiPEC. The supply and return headers are shown as cyan and red piping running underneath the PEBB bays. The two sets of PEBB bays can be seen with the larger PEBB6000s in the three left-hand stacks and the smaller iPEBBs in the three stacks to the right.

As can be seen in Figures 11 and 12, the power density of the PEBB should include not only the dimensions of the PEBB drawers themselves, but also the supporting structure, electrical back-plane, and cooling system. In this case, the volume of a four-PEBB bay using PEBB-6000 technology is 8.67 m^3; to this should be added the impact of the cooling system that is external to the NiPEC.

VI. APPLICATION

Smart Ship Systems Design (S3D) is a software environment for the modeling and analysis of Navy shipboard distribution systems. Systems are logically modeled in the software using component representations which can then be physically arranged in three dimensions within the ship virtual model as well. S3D provides power flow level simulation of power and energy flows in electrical distribution, piping, and mechanical systems. Work is ongoing to expand this to a full dynamic simulation.

S3D is integrated into the Leading Edge Architecture for Prototyping Ships (LEAPS), which is the Navy's data repository for ship information. All the Navy's early-stage design tools are integrated with LEAPS, so that information generated within any one tool is available to all other tools. In this way, ship design information created by another Navy tool is available to S3D, and ship system design information created in S3D is available to other tools.

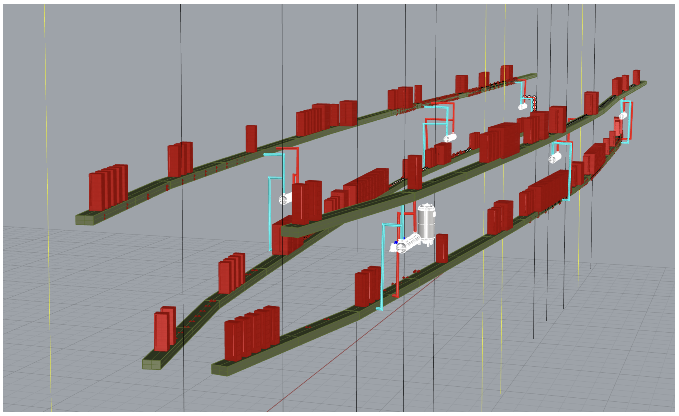


Fig. 11: Full NiPEC cooling system design showing PEBBs, PEBB bays, piping, heat exchangers.

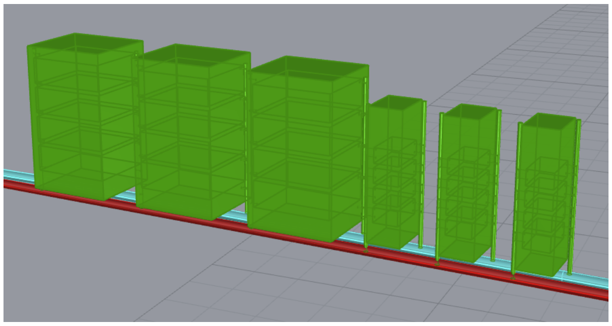


Fig. 12: NiPEC power train example with cooling.

S3D contains within it a large library of mathematical models of various pertinent ship components such as generators, power converters, switches, cables, pumps, chillers, piping, motors, shafts, propellers, and more. There are essentially three categories of components: notional components, which can be parameterized to represent a wide variety of like components, e.g. a generic gas turbine engine; non-notional components, which are parameterized to represent a specific piece of equipment, e.g. a GE LM2500 gas turbine engine; and self-sizing components, which contain sizing algorithms that parameterize the dimensions and weight of the component based on a set of inputs. Any one component item, such as a gas turbine engine, can use the same mathematical model but be parameterized as notional, non-notional, or scalable.

The ship architecture models shown in Figures 9 and 10 were created using S3D.

One application of VPP is to create a scalable model of a PEBB-based power converter using VPP as the engine to create the behavior models to allow scaling of components with such inputs as voltage, power and cooling water temperature. Physics-based scalable models are a desired feature in the development of S3D, improving usability in the design of new-concept systems.

VII. CONCLUSIONS AND FUTURE WORK

To summarize, this study investigated the performance of an MMC system for shipboard PEPDS applications. The results showed that the voltage level, incoming water coolant temperature, and intrinsic power value all significantly impact the system's power density and efficiency. When deciding on the operational characteristics of the system, it is critical to consider the trade-off between power density and efficiency carefully. These findings should be considered in future research and development initiatives because they have significant implications for designing and optimizing MMC systems for shipboard PEPDS applications. This study demonstrates that lower coolant temperatures and higher voltage levels result in higher power densities.

The various drawers containing the PEBB/iPEBB LRUs, and additional passive LRUs, should be optimized as part of the overall system optimization. Modeling the NiPEC sections to include the electrical backplane into which the individual drawers connect, the structural support provided by the cabinet structure, and the cooling system components external to the drawers are the next steps in this work.

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