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MBSE Approach to Early Naval Ship Design Exploration with Power Electronic Power Distribution System in Power and Energy Corridors

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***Abstract*—The concept development of any system includes the definition of various parameters of interest and determination of the threshold (satisfactory) and goal (desired) value for each. These are classically organized into Measures of Effectiveness, Measures of Performance (MOPs), & Technical Performance Measures (TPMs). These form the basis of performance requirements, the means for evaluating design, and the measure by which systems are validated. A cross-cutting sub-set of MOPs and TPMs, Key Performance Parameters (KPPs) can define the trade space within which to optimize the emerging solution. Applying this systematic approach is substantially complicated when the system of interest aims for unprecedented capabilities from emerging technologies, which is the situation for electric ship research. This paper presents an Integration Framework that effectively maps out a process leading to defined parameter objectives, which is being developed and used in the U.S. Department of Navy sponsored Power Electronic Power Distribution System (PEPDS) research initiative. The method then integrates the Model-Based Systems Engineering (MBSE) system model with genetic algorithm trade space exploration tools.**

***Index Terms*—MBSE, Digital Engineering, Technical Performance Measures, Trade space**

I. Introduction

The concept development of any system includes the definition of various parameters of interest and the determination of the threshold (satisfactory) and goal (desired) value for each. These are classically organized into Measures of Effectiveness (MOEs), Measures of Performance (MOPs), and Technical Performance Measures (TPMs), along with a crosscutting subset of MOPs and TPMs identified as Key Performance Parameters (KPPs). These form the basis of performance requirements, the means for evaluating design, and the measure by which systems are validated. They define the trade space within which to optimize the emerging solution. This is challenging in routine development and substantially complicated when the system of interest aims for unprecedented capabilities from emerging technologies, which is the situation for electric ship research. This is especially the case when system designs are being evaluated based upon the use of hardware for which no actual measured data exists.

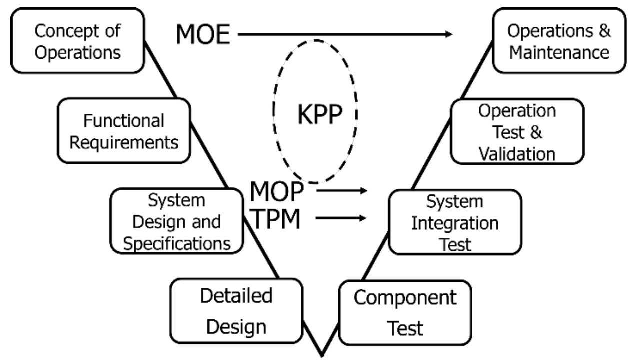

Fig. 1: Systems engineering “Vee” adapted from reference [3].

This paper proposes processes that will enable the development of a Power Electronics Power Distribution System (PEPDS) within power and energy corridors that is both feasible and viable for the navy shipboard application. These processes were first introduced in [1], which is also connected to the Model Based Systems Engineering (MBSE) approach to baselining an architecture for a PEPDS, described in [2]. The combined result of these works is a structured systems engineering approach to ensuring success over the life cycle of such a system.

Systems engineering has traditionally represented this methodology in a "Vee" as shown in Fig. 1 [3]. This model shows how the parameters of interest track and shape the system development as it matures, emphasizing the interdependence and integration of various stages. The "Vee" model underscores the importance of considering system requirements, design, and testing concurrently for a cohesive system development lifecycle. *Thresholds of performance parameters play an important role in bounding the feasible solution space.* By defining specific limits and criteria, these thresholds establish the boundaries on the electrical, thermal, and physical (electro-thermal-physical) characteristics of both the system and its building blocks. They also serve as reference

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points, ensuring that the proposed solutions not only meet the specified requirements but align with the intended performance standards.

The move towards naval ship electrification [4] is driving unprecedented changes into the power and energy delivery and distribution systems of future, highly electrified naval ships. Electric ship research is also following the trends of grid modernization, which include the need for more efficient, reliable, and resilient power and energy delivery, and are enabled by increased penetration of power electronics-based generation, point of load services and Distributed Energy Storage (DES) management. The U.S. Navy is leveraging Digital Engineering advancements to introduce an agile Integrated Power and Energy System (IPES) that enables electrified ship war-fighting capabilities [5] and to realize new shipbuilding approaches that integrate *modular building block-based system realizations of IPES into the earliest stages of ship design. These building blocks are power electronics-based* [6].

The U.S. Department of Defense Digital Engineering Strategy (2018) defines Digital Engineering as an integrated digital approach that uses *authoritative sources of system data and models* as a continuum across disciplines to support lifecycle activities from concept through disposal [7]. If Digital Engineering is to have value, it should provide better, cheaper, and faster techniques for making engineering decisions and enable early design exploration capability at the system level even before the determination of the final KPP values that drive the design of equipment comprising the system (well ahead of the beginning of detail design). To elaborate further: Decisions need to be made by stakeholders, such as shipbuilders, navy procurement agencies, and other decision-makers, well ahead of the engineering decisions made after a procurement is in place. Progress towards the development of Rapid Ship Design Environment (RSDE) tools to help stakeholders determine the impacts of low-level procurement decisions on ship system feasibility and viability still lack the capability of connecting RSDE process outcomes to stakeholder needs [8], [9].

The PEPDS is a power, energy, and control and distribution concept that is enabled by Office of Naval Research investments in high density, modular power electronic conversion building blocks to realize navy shipboard electrical IPES [10] . Drawers that contain building blocks, or are building blocks themselves, are referred to in this paper as PEPDS building blocks.

The navy integrated power and energy corridor, or NiPEC, eliminates overhead redundancies (and inefficiencies) among IPES equipment in structural support (thermal management, cabling, mechanical support, etc.) by enabling integrated, shared use structures and systems [11], [12]. The NiPEC is integrated into the ship bulkhead and deck structure. The NiPEC-PEPDS is the physical implementation of the PEPDS within the NiPEC and is a sub-system of the ship level System of Systems (SoS). The combination of a PEPDS implementation within the NiPEC will be referred to hereafter as NiPEC-PEPDS.

The definition and utilization of KPPs across engineering disciplines and activities offers an excellent opportunity to realize the benefits of early design space exploration to decision-

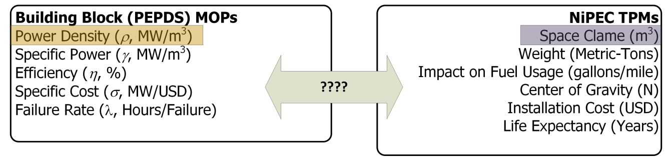

Fig. 2: Technical measures (KPP) gap

makers. Fig. 2 illustrates the gap between NiPEC-PEPDS level TPMs and the MOPs associated with lower-level building blocks of the PEPDS. The NiPEC-TPMs represent aspects of performance that are important to naval architects, since they relate directly to the accomplishment of the ship mission. For example the Space Claim TPM for NiPEC is the amount of space that can be allocated for PEPDS functionality after sufficient room for placement of mission essential equipment has been determined. As another example, Fuel Usage Impact, correlates directly to limitations that must be placed on the mass (or hull displacement) of the NiPEC-PEPDS equipment. On the other hand, building block MOPs are meaningful measures of the goodness of one PEPDS implementation over another.

The meaningfulness of the building block MOPs are arbitrary if not linked to the TPMs. The identified MOPs are meaningful to the suppliers of equipment comprising the PEPDS. For example, MOPs such as power density, specific power and efficiency, can be effective during the procurement process, if these measures are linked to the TPMs. Establishing this linkage is a key challenge. The work of this paper connects to a previous description of systems engineering techniques applied to the shipboard integration of various IPES realizations, including NiPEC-PEPDS. [1]. This paper focuses specifically on the NiPEC-PEPDS.

This paper contributes an innovative approach to bridging the gap illustrated in Fig. 2, that relies first upon the development of parameters and their threshold and goal/objective values. The approach is being developed for use within the U.S. Department of Navy sponsored PEPDS research initiative. The method integrates the Model-Based Systems Engineering (MBSE) system model [2] with genetic algorithm-based trade space exploration Model Based Engineering (MBE) tools that feed into a ship level Set-Based Design (SBD) to achieve a RSDE with full traceability between hierarchical technical measures. A use-case is described, which illustrates an application of the method.

The main focus of this work is on connecting the PEPDS MOPs to the NiPEC-PEPDS TPMs, columns 3 and 5 of Table I. The connection between column 3 (PEPDS MOPs) and column 5 (NiPEC-PEPDS TPMs) generally has to do with the identification of feasible design sets, i.e. those design sets that will fit within ship hull constraints and that will meet the minimum mission requirements. Future work will address the connection between column 4 and 5, which has to do with system-level analysis and extractional of operational KPPs under various time-dependent, event-driven and probabilistic analyses of the ship system utilizing the identified subset of feasible NiPEC-PEPDS designs.

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TABLE I: NiPEC-PEPDS Performance Parameters. **KPPs are starred** (*)

MOEs	MOP Categories	PEPDS MOPs	NiPEC-PEPDS MOPs	NiPEC-PEPDS TPMs
P & E Delivery	Affordability	Active LRU Cost, **Power Train Specific Cost***	**Operational Cost***	Installation, Maintenance, Implementation, Training, & Upgrade/Alteration Time-Cost
	P & E Transport	**Power Train Power Density*, Specific Power* & Efficiency***, ESD Energy Density & Specific Energy	Discharge Capacity, Pulse Power Characteristics, Operability, Robustness	Installed Point of Service Power, Heat Load, **Space Claim*, Weight*, Center of Gravity*, Fuel Usage Impact***
	Adaptability	Active LRU & Drawer Flexibility	Adaptability	Redundancy, Reconfigurability
	Survivability	**Power Train Failure Rate***	Robustness, **Invulnurability*, Recoverability*, Resilience***	Overload Capacity, Loss of Coolant Capacity, Rate of Recovery, **Time to Recover*, Instantaneous Operability***
RAM	Reliability, Availability, Maintainability	LRU MTBF & MTTR	Inherent Availability, System Failure Rate, **Restorability***	Drawer Repair Time, Time to Restore*, Maintenance Burden, Operational Availability, Life Expectancy
Safety	Personnel, Equipment, System	LRU Transportability & Lift-ability, Insulation & Ground Resistance, Dielectric Withstand	Meant Time to Contain*, Mean Time to Isolate*	Leakage & Dielectric Absorption Current, Containment, Partial Discharge, Ground Resistance

II. Technical Measurement Organization

The classic abstract hierarchy for technical measures has three formal tiers and an orthogonal tier spanning set: MOEs, MOPs and TPMs. The most abstract technical measure tier consists of MOEs which describe the requirements for the system's mission accomplishment. MOEs should provide insight into at least one operational objective or mission requirement. The middle technical measure consists of MOPs, which derive from MOEs usually with several MOPs for each MOE. MOPs should be traceable to system level performance requirements, goals, risk, or issues. Under the classical definition, the most detailed (least abstract) technical measure tier consists of TPMs which *should* derive from the system's MOPs in the classical hierarchy.

The naval ship is a SoS having ship-level MOEs, such as *Mission Accomplishment* that are distinct from those MOEs assigned to the NiPEC-PEPDS. The NiPEC-PEPDS is a part of the overal ship SoS having a distinctive MOE of *Power and Energy Transport*, which breaks down into multiple MOPs and TPMs as described in Table I. At the same time, there are ship-level MOEs, such as Reliability, Availability and Maintainability (*RAM*) and that *Safety* which the specific *RAM* and *Safety* MOEs of the NiPEC-PEDS feed into. Additionally, there will be a specific ship-level TPMs, e.g. *Mission Equipment Space* and *Hull Displacement* to which the NiPEC-PEPDS level TPMs, *Space Claim* and *Weight* contribute. Since the PEPDS implementation of the IPES within NiPEC is comprised of Drawer-based building blocks (as will be discussed later) there are MOPs associated with those building blocks (*PEPDS MOPs*) as well as MOPs associated with the integrated use and operation of the PEPDS building blocks in NiPEC (*NiPEC-PEPDS MOPs*). A hierarchy between NiPEC-PEPDS TPMs and the build block MOPs is difficult to establish, but will be essential to assurance of feasible implementations of NiPEC-PEDS, the informing of enabling research investments and the ultimate procurement of PEPDS hardware for shipboard installations. Programs typically identify TPMs early in the project, often during the proposal, but they can also emerge during test and integration stages. However, if TPMs of any system are well-defined early on, they can help isolate a feasible sub-set of solutions within the SoS. Threshold and goal values associated with these TPMs should tie back to ship system-level constraints and mission/global-level requirements. It should be noted that MOPs support trade studies, feasibility evaluations, quality, and risk management. However, the MOPs themselves may not reveal the features that stakeholders really care about. Specific MOPs may be also be competitive, emphasizing the need for early stage design studies to determine MOP ranges that correspond best to the realization of TPMs of a feasible ship.

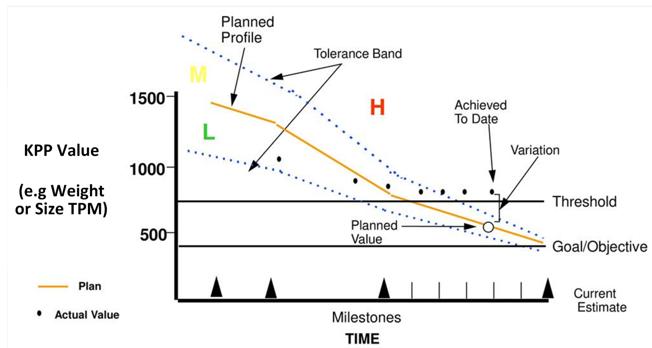

Fig. 3: Technical Measure Profile Illustration

KPPs include both TPMs and MOPs and should be utilized to establish threshold values for mission accomplishment, performance, and operational factors. For these technical measures to have any effect on managing the technical work, KPP values that both ensure program success and drive innovation must be quantified early during system design stages. Fig. 3 shows a generic technical profile. The profile defines a threshold which is the value the program believes must be obtained in this measure for success, such as maximum Weight or Space Claim (both TPMs of the NiPEC-PEPDS). The threshold shown in Fig. 3 is a maximum value, but it may also be a minimum value. If the threshold value is not achieved, it could result in the acquisition program being terminated. The greatest risk lies in the fact that goal/objective and threshold values are undefined or ill-defined until later stages of development programs. Since early-stage development always involves substantial uncertainty, tolerance bands, between goal and threshold levels, should be well-informed to balance Science and Technology (S& T) investments against stakeholder needs and program risks. It is common for government agencies tasked with promoting and funding research and development, to link the success of a program to KPP threshold and goal values that are either experiential or highly aspirational. Unfortunately, if these KPPs apply to a lower-level sub-system of SoS, and do not correlate to TPMs of the larger system that they are enabling, such an approach has limited value to stakeholders.

The PEPDS is comprised of lower-level building blocks that can be configured into a wide range of *Power Trains*, which are a higher-level building block within NiPEC that describes power/energy delivery paths between power/energy sources of supply and load points of usage. At the lowest level, the Power Trains are an arrangement of *Line Replaceable Units (LRUs)*. These LRUs also serve as a point of new technology insertion which should enable NiPEC-PEPDS capability(s). Determining what has been achieved-to-date alone is a remarkable challenge. For example, the U.S. navy's investment in Power Electronic Building Block (PEBB) and Navy Integrated PEBB (NiPEBB) development feeds into the PEPDS research initiative [13]–[19]. These LRU first articles exist, with quantifiable MOPs and progression towards increase Technical Readiness Levels (TRLs). However, to date, there are no 'first article' NiPEC-PEPDS implementations from which actual measurements can be made to gauge the feasibility and viability of these systems based upon the LRU MOPs.

The process of determining the goal/objective and threshold values of both higher- and lower-level KPPs is a crucial aspect of systems engineering. To determine their goal/objective and threshold values, a combination of methodologies, tools, and techniques are used. A typical approach is top-down performance requirement allocation, where system performance requirements are allocated to its components [20]. Such approaches amount to a kind of top-down budgeting, where the program first estimates the technical measure values required, and then budgets a portion of that down the abstract hierarchy of functions and/or structures according to often unstated assumptions about what those lower components may achieve. In actual practice, such budgets amount to a first approximation guess, as a placeholder for an unverified capability, and components negotiate from there as facts emerge. This approach is inconsistent with an MBSE approach because it divides the interests of components.

The first approximation is typically based on "expert opinion". Forecasting for technical performance has included eliciting expert opinion. In many real-world forecasting exercises, statistical techniques may not be viable or practical, and expert judgment may provide the only basis for a forecast [21]. Considering the 'bottoms-up' approach of the PEBB-based PEPDS, the above approach introduces a unique conundrum. "Expert opinion" in this case assumes that the achievement

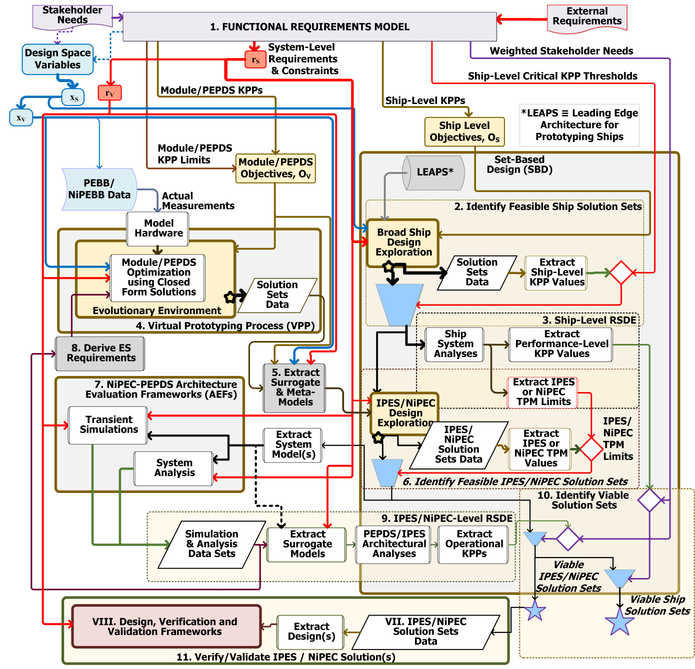

Fig. 4: Integration Framework for Solution Space Exploration

of building blocks with high KPP levels (assuming the goal/objective of Fig. 2 is set to a maximum and the threshold is set to a minimum) will result in enthusiastic yet unverified system-level TPM values. The technical measure abstract hierarchy contains an inherent fallacy: each component of a higher tier has a one-to-many relationship with the lower tier's components—with no interaction between measures that derive from different higher tier components. Focusing on a branch of the technical measure abstract hierarchy inevitably has repercussions within other measures that are out of focus due to interactions between measures and the behaviors/structure that they measure.

It is in addressing this last problem that the methodology proposed by this paper offers a true innovation in the context of NiPEC-PEPDS. An Integration Framework for NiPEC-PEPDS solution space exploration is shown in Fig. 4. By aligning functional requirements with these PEPDS technical measures, this paper establishes a foundation for addressing the challenge at hand: offering an effective solution to calculate the threshold and objectives of the NiPEC-PEPDS performance parameters.

III. Method

A. Overview

While technical measurement is a key focus of systems engineering, it does not define measures, determine thresholds and goals, or measure achieved-to-date in absentia from other technical disciplines. A major benefit of systems engineering is to break the stovepipes that naturally separate different kinds of work—to stovepipe systems engineering would be to make the solution part of the problem. MBSE, MBE, and Digital Engineering all utilize models to inform and integrate technical work. At the highest level, the Integration Framework illustrated in Fig. 4 shows how solutions can be derived from the Functional Requirements Model of [2]. The Functional Requirements Model identifies the parameters against which solutions will be assessed. Parameters relevant to the purposes of this paper, i.e. introducing the Integration Framework and illustrating a part of that Framework with a use-case study, are shown in Table I.

The approach of Fig. 4 can be made a reality if the trade space can be defined as a solution space whose dimensions are the various measures, and the thresholds and goals as points along those dimensions. A specific “solution” is the vector with goal/objective and threshold values, and actuals for each measurement of these values—fed into and arising from discipline specific models. Defined this way, the trade space has very high dimensionality but is very sparsely populated. To search this trade space is to search for the vector that provides the best overall value. This is precisely how a genetic algorithm works, with the vector’s point addresses serving as genes and the optimal value defining the objective function. The NiPEC-PEPDS solutions space therefore begins with an evolutionary environment where design space variables (defining the exploration space) are inputs to a Virtual Prototyping Process (VPP), as informed by stakeholder needs. The design exploration variables include the exploration of the value of the S&T investments in enabling LRU building blocks of the PEPDS or Modules [22], [23], for which actual performance, to some TRL, has been measured. These explorations are constrained by requirements and constraints identified and defined through the Functional Requirements Model. The exploration space is enabled by the searching for designs that meet competing optimizing objectives, derived from building block level KPPs identified in Table I.

B. Motivation

Realization of the U.S. Navy’s vision for the NiPEC-PEPDS instantiation of an IPES presents an important demonstration use-case for the development of a suitable Integration Framework for MBSE, MBE, and Digital Engineering. IPES is the means whereby the navy can achieve competing objectives of smaller ships, increased war-fighting capability, and reduced manning through electrification. Ship loads include installed Mission Loads (MLs) of a significant power level, Propulsion Motor (PM) and pulsed Pulsed Power Loads (PPLs), in addition to requisite Ship Service Loads (SSLs), which are generally ac loads fed from a Low Voltage Distribution System (LVDS). In aggregate, installed loads will far exceed the installed Power Generation (PG) capacity. Some of these deficits are made up by bulk Energy Storage placement in specific zones and by DES throughout. The IPES is a system within the larger ship-level SoS that is responsible for the dependable electrical power and energy delivery.

A notional NiPEC-PEPDS is shown in Fig. 5. The NiPEC-PEPDS is a zonal electrical distribution system, where electrical and physical zones of protection align with the ship layout to ensure survivability. The NiPEC-PEPDS concept is to have an inter-zonal MVdc bus on port and starboard sides for power and energy transport to any zone of the ship. Similar LVdc (nominally 1kV) longitudinal buses may also be included

TABLE II: PEBB/NiPEBB Active LRUs

PEBB/ NiPEBB	Description	Voltage	Ref.
P1000	1.7kV SiC MOSFET based Full-Bridge	1kV	[13]
P6000	10kV SiC MOSFET based Full-Bridge	6kV	[14]
HB P6000	10kV SiC MOSFET based Half-Bridge	6kV	[15], [16]
iPEBB	Integrated multi-stage CLLC isolated dc-dc converter (DCx), hard-switch Outer Bridgers (OBs) on common substrate	1kV	[17], [18]
DCx	Isolated dc-dc converter (DCx) section of iP	1kV	[19]
OB	Hard-switched Outer Bridge of iP	1kV	[19]

in architectural implementations of the the NiPEC-PEPDS. Additionally, the PM and some of the MLs and critical SSLs are dual-fed from port and starboard-side feeds. Survivability is enabled by disconnect switches (DCNs) that can electrically isolate sections of the MVdc bus between bulkheads, and by Solid State Circuit Breakers (SSCBs) on the LVdc inter-zonal bus that provide current limiting under fault conditions and provide galvanic isolation to damaged portions of the bus. The DCNs do not have the capability to break dc current, but rely upon upstream MVac/PG to MVdc power conversion to drive currents to zero before they are allowed to open during fault conditions. It should be noticed that the system shown in Fig. 5 is just one architectural implementation of the NiPEC-PEPDS. Not all architectures under consideration will have this breaker-less protection philosophy and would therefore require MVdc SSCBs instead of DCNs in order to ensure survivability (resulting in a breaker-based protection philosophy informed architecture).

The Office of Naval Research and Department of Energy investments in PEBB development have resulted in a 6kV rated PEBB, or PEBB 6000, that utilizes 10kV rated Silicon Carbide (SiC) MOSFET dual Modules. The Office of Naval Research has also invested in the development of the integrated Power Electronic Building Block (iPEBB) that utilizes SiC MOSFET based implementation of a four-stage isolated dc-dc converter in a high density package where switching and passive elements on each side of the switching frequency isolated converter share a common integrated substrate on baseplate for heat extraction [24]. Development efforts have brought the PEBB 6000 to TRL 3, through system-level demonstration programs [15]. The iPEBB is progressing towards TRL 3, through innovative approaches to multi-disciplinary challenges [17]–[19] and the long-term plan includes development of a family of similarly highly power dense and modular solutions for PEPDS, or NiPEBB, to fully realize the NiPEC-PEPDS.

The NiPEC-PEPDS utilizes PEBB/NiPEBB for all power conversion and distribution functionality within the NiPEC, represented in Fig. 5. Flexible, maintainable and adaptable Module functionalities are realized through Drawer-based PEPDS building blocks, Table III, containing active LRUs

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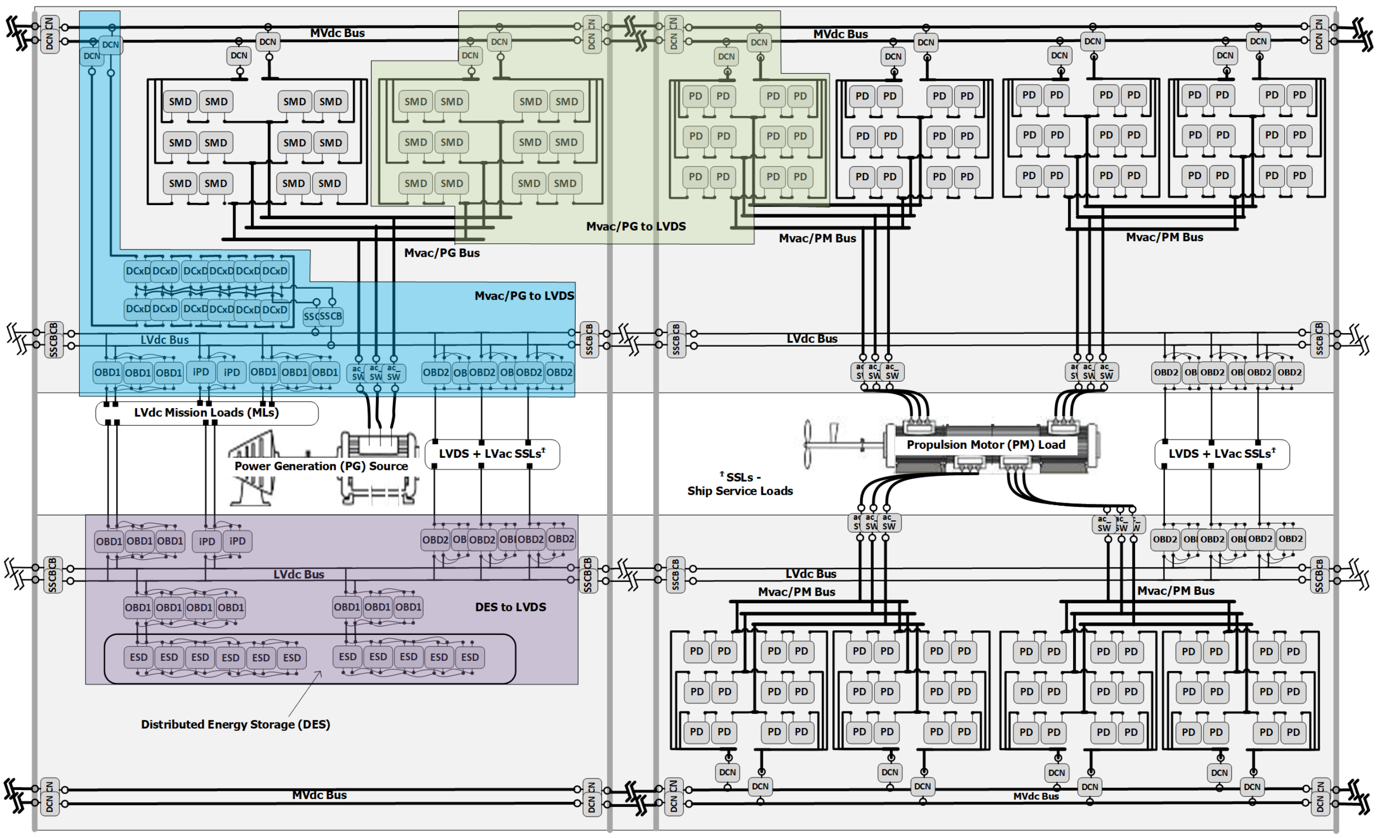

Fig. 5: A notional implementation of NiPEC-PEPDS across multiple zones showing connections to a MVac PG source, variable frequency, variable MVac PM load, LVdc MLs and LVDS feeding LVac SSLs. Three of the Power Train Types are shown: **MVac/PG to MVac/PM** (Green), **MVac/PG to LVDS** (Blue) and **DES to LVDS**, where LVDS implies LVdc MLs and LVDS with LVac SSLs. (Violet)

of Table II. Active LRUs are those LRUs that contain active switching power electronics and enable the functionality of power and energy conversion. This terminology is utilized to distinguish LRUs such as PEBB/iPEBB from Passive LRUs that provided filtering of conducted EMI and energy storage. The Active LRUs enable a maintainable and scalable PEPDS within the NiPEC. The extent to which active LRUs enable a wide range of power conversion functionality, economies of scale are realized, manifested by high goal/objective values of the affordability KPP, specific cost (σ, MW/USD).

C. Method

As proposed in [25], IPES design space exploration should occur within an evolutionary environment to enable multi-disciplinary optimization. Because IPES or NiPEC is integral to the whole ship design, design exploration of the IPES/NiPEC must connect with a total ship design environment. This concurrent exploration is realized through the use of Smart Systems Design (S3D) [26], a Digital Engineering environment developed for the modeling and analysis of Navy shipboard distribution systems, integrated with the Navy's total ship design environment, RSDE. Fig. 4 shows a process that utilizes S3D for broad ship exploration at ship level leading to the downselection of viable IPES/NiPEC implementations through SBD [27].To clarify further, the broad ship exploration is a multi-disciplinary design process that assesses a range of arrangements of essential and mission critical equipment within a ship hull design. For the purposes of the discussion of this work, the broad ship design determines the number damage control zones, associated bulkheads, and the placement of equipment with these zones. Referring to Fig. 4, execution of steps 2 and 3 results in the NiPEC-PEPDS TPM goal/objective and threshold limits (on the right hand side of the flow diagram) against which the building block and subsequent architectural implementations of PEPDS, with associated MOPs/KPPs, (determined by the flow on the left hand side of the diagram) are assessed. This unique Integration Framework (Fig. 4), proposed by the authors, is described in more detail by the execution steps of Table IV.

The novelty of this MBSE approach is that it maintains traceability of all IPES/NiPEC level decisions through design space variables, x_V, sub-sets of the ship system level design space variables, x_S, or technology insertion variables. Regarding the latter, x_V will include PEBB/NiPEBB types, power conversion topological implementations, control and thermal management approaches, and protection philosophy (e.g. breaker-based vs. breaker-less protection). The process is designed to enforce transparency between design space variable inputs (x_V) and performance measure outcomes (KPPs and TPMs) and, ultimately, *to bridge the technical measures*

TABLE III: PEPDS Building Blocks (Drawers) *

Drawer	Symbol	Description
Sub-Module Drawer	SMD	PEBB w/ sub-module inductor & additional sub-module capacitance
PEBB Drawer	PD	PEBB w/ sub-module inductor
DCx Drawer	DCxD	Isolated DC-DC Converter (DCx) part of iPEBB
iPEBB Drawer	iPD	iPEBB w/ no load disconnects
dc-dc OB Drawer	OBD1	Outer Bridge part of iPEBB configured as a non-isolated dc-dc converter w/ EMI filter & no load disconnects
dc-ac OB Drawer	OBD2	Outer Bridge part of iPEBB configured as a non-isolated dc-ac converter w/ EMI filter & no load disconnects
ES Drawers	ESD	Discrete ES cells arranged in Drawers
ac Disconnect	ac_SW	Disconnect Switch for MVac fault protection and repair
dc Disconnect	DCN	Disconnect Switch for MVdc fault protection and repair
Solid State Circuit Breaker	SSCB	Current Limiting & Disconnect Switch for LVdc fault protection and repair

* Building Blocks are Drawer-based and include active and passive LRUs, thermal management and basic or reinforced insulation as required.

gap represented in Fig. 2.

D. NiPEC-PEPDS Use-Case Example

The remainder of this paper focuses on the PEPDS implementation of the IPES within the NiPEC. Specifically, three watertight bulkhead sections of a notional ship are modeled including a gas-turbine generator source and a propulsion motor load, along with the PEBB-based NiPEC segments required for distribution of the power. Power is distributed through the ship as MVdc power at 12 kVdc. The engine room, containing the generator, has a length of 14.04 m, deck heights of 3 m, and breadths at the second deck ranging from about 17.5 m to 17.0 m from the forward to aft bulkheads. The gas-turbine generator is a GE LM500 [28], rated to produce 4.57 MW of power at 4.16 kV(rms). For the purposes of this study it is assumed the GE LM500 can re-wound to produce 7kV(rms) to better match the generator with the 12kVdc bus, without impact to the size/weight. The motor room, containing the propulsion motor, has a length of 8.0 m, breadth of approximately 19.0 m, and deck heights of 3 m. The propulsion motor load is rated at 19.0 MW 12-phase MVac. The ship sections and loads can be seen in Fig. 6.

Fig. 7 shows the VPP, PEPDS Drawer metamodel extraction and NiPEC Size, Weight, Area and Power versus Cooling (SWAaP-C) analysis, (steps (3)-(6) of the Integration Framework) and the tie-back to the Functional Requirements Model (step (1)). Execution of steps (4)-(6) identifies feasible NiPEC-PEPDS design solutions, i.e. those designs whose TPMs fall within the TPM goal/objective and threshold levels, where values of for these levels are the result of a specific ship design study. SWAaP-C solution space exploration is executed in the S3D environment. A broad study of different Power Trains (Fig. 5) and Power Train solutions, as a function of x_V, utilizing the process of Fig. 7 will inform the PEPDS building block KPP goal/objective and threshold levels and bridge the gap illustrated in Fig. 2.

The Leading-Edge Architecture for Prototyping Ships (LEAPS) [29] is the Navy's data repository for ship design

TABLE IV: Integration Framework Execution Steps

Step	Description
1	Use Functional Requirements Model to connect stakeholder needs and external requirements to ship-level requirements and constraints r_S and ship-level and Module/PEPDS-level KPPs.
2	Perform broad (or specific) ship design exploration n RSDE to identify feasible ship design solutions against ship-level KPP thresholds and execute ship-level RSDE to determine NiPEC TPM thresholds.
3	Execute VPP to produce Pareto-optimized performance space of PEPDS building blocks (defined by stakeholder derived PEPDS KPPs and guided by trade study informed KPP objective and threshold values) versus design space.
4	Extract data-driven surrogate models of physics-based behavior and PEPDS building block metamodels for incorporation into S3D for NiPEC solution space exploration.
5	Perform SWAaP-C to identify feasible NiPEC solution sets.
6	Extract dynamic and quasi-dynamic system models from the NiPEC feasible solution sets
7	Perform NiPEC-PEPDS architecture dynamic and static analyses in offline Architecture Evaluation Frameworks (AEFs).
8	Use operational KPP outcomes of AEF operability and survivability analyses to derive additional Energy Storage requirements as inputs to subsequent iterative executions of steps (3)-(7).
9	Execute IPES/NiPEC-level RSDE to produce NiPEC-PEPDS MOPs.
10	Narrow down to the viable NiPEC solutions sets using MOPs from the AEFs. Iterative executions of (7)-(10) will help identify the KPP threshold/objective levels required to narrow down to the best architectural implementations.
11	Extract MOP and TPM actuals verify and validate from a viable (or feasible) solution set.

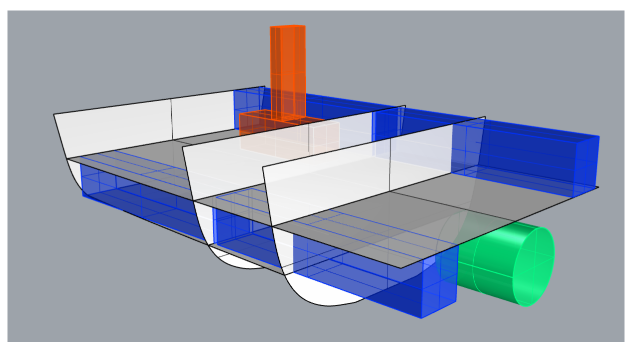

Fig. 6: Case Study: example watertight sections with a single modified LM500 gas turbine PG source with stacks, orange, a single PM load, green, w/ reserved space for the two NiPECs (port & starboard), blue.

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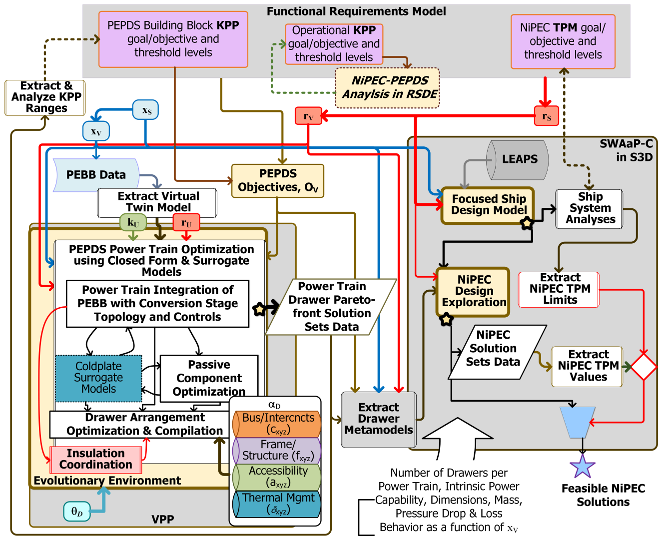


Fig. 7: PEPDS Power Train Drawer VPP-fed SWAaP-C of NiPEC (w/ interfacing metamodel of selected Power Train Drawer solutions)

information. A ship design stored in a LEAPS database contains all data relative to a ship design such as properties and geometry for ship components, interconnects (i.e. shafts, piping and cables) and structures (i.e. hulls and bulkheads), behaviors, and simulation results. Data stored in LEAPS that is compliant with the Formal Object Classification for Understanding Ships (FOCUS) is available across programs for other functional analyses such as seakeeping, stability or survivability. FOCUS is the product metamodel that defines how to store properties within the LEAPS database, making them available to FOCUS-compliant software tools such as S3D [30]. The S3D model of a specific ship emulates the electro-thermal and performance of the shipboard systems. Physical space claim, mass and location of Program of Record (PoR) elements are populated within LEAPS by RSDE. The specific ship design model is populated with the PGs, DES's, MLs and SSLs required to meet the ship's mission. The MLs and SSLs are modeled in electrical, thermal, mechanical, and physical domains. The physical domain is where arrangement of equipment in ship spaces is accomplished.

For the NiPEC-based ship design, space is reserved at the early stages of the design for NiPEC across multiple damage control zones of the ship, distributed longitudinally from bow to stern. In later stages of design, this reserved space is populated with the appropriate equipment according to the installed sources and loads in each zone. This space allocation establishes the first TPM for the NiPEC. The reserved space can be seen in Fig. 6 as a long blue block on decks 2 and 3. Further forward in the ship, where there is more vertical space, the corridors are separated by an additional deck. The reserved space is intended to be sufficient to contain all the components that make up the NiPEC plus all required access area for operation and maintenance of the equipment. It is permitted for access areas of multiple pieces of equipment to overlap.

1) Virtual Prototyping Process: The NiPEC will be populated with PEPDS building blocks, listed in Table III, containing the active LRUs of II, to realize the necessary power and energy conversion and distribution paths between installed sources and loads in each zone. The authors have developed a unique Virtual Prototyping Process, VPP, for IPES solution trade studies [22], [23]. PEPDS building blocks comprise what has been defined as a Power Train. The PEPDS building block KPPs of Table I apply to the Power Trains. The Power Train is the NiPEC-installed set of Drawers (the building blocks) comprising two or more power conversion stages (and isolating switches as necessary) between a point of source connection and a point of load connection. It is important to make this distinction, as the Power Train does not necessarily represent multi-stage power/energy conversion of all power/energy supplied by the source and all power/energy consumed by the load(s).

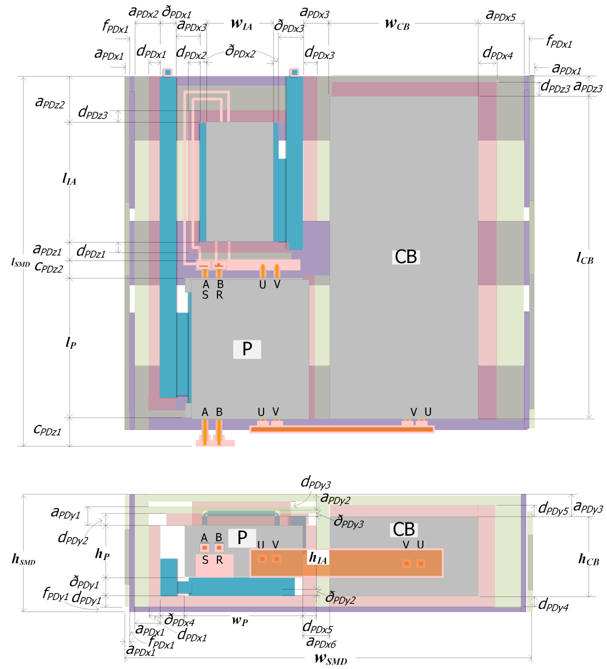
Fig. 5 shows three possible Power Trains: MVac/PG to MVac/PM, MVac/PG to LVDS and DES to LVDS. The first MVac/PG to MVdc power stage converts fixed frequency 3-phase MVac/PG voltage to MVdc bus voltage. The second stage is a Variable Frequency Drive (VFD) that converts MVdc bus voltage to 3-phase MVac/PM voltage that is a variable volgage and frequency load interface. The first conversion stage of the MVac/PG to LVDS Power Train is the same MVac/PG to MVdc power conversion stage. This is followed by an internal power stage forming isolated MVdc-MVdc conversion between the MVdc bus and a NiPEC internal, LVdc bus. The final stage, between LVdc and LVDS, consists of multiple ML point of load interface converters and point of interface to the LVDS feeding LVac SSLs. A solution exploration space for PEPDS Power Trains within the NiPEC can be created through combinations of PEPDS Drawer design space variables, x_V, as defined by Table V. The third DES to LVDS power train incorporates ESDs as the energy source is useful for developing energy density and specific energy MOPs for associated PEPDS Drawers. There will be unique KPP goal/objective and threshold values for each Power Train. The process of Fig. 7 is executed separately on each Power Train type, across a design space defined by x_V in order define the NiPEC-PEPDS solution sets (corresponding to each unique set of x_V values)leading to final sets of feasible NiPEC solutions.

The Power Train is characterized by the *intrinsic power throughput capability,* P_{oi} *(*T_A*,mfr)*, of the sets of Drawers comprising a power conversion path between points of source and load connection, through which power/energy is delivered. The intrinsic power represents the nominal installed capability of the Power Train Drawers as a function of the inlet water temperature, T_A, and mass flow rate, *mfr*, (in *kg/s*), where power flow is through only one active LRU in its power conversion configuration. This methodology is useful in correlating the KPPs of PEPDS building blocks to end-use installation (NiPEC) TPMs as a function of the NiPEC-level thermal management capability (also a TPM with interdependencies to the other TPMs shown in Fig. 2). In this way, the capacity of active LRUs for power/energy delivery connect to coolant approach ($M_{\eth}$), topology (M_T) and control approach (M_c) design space variables of Table V.

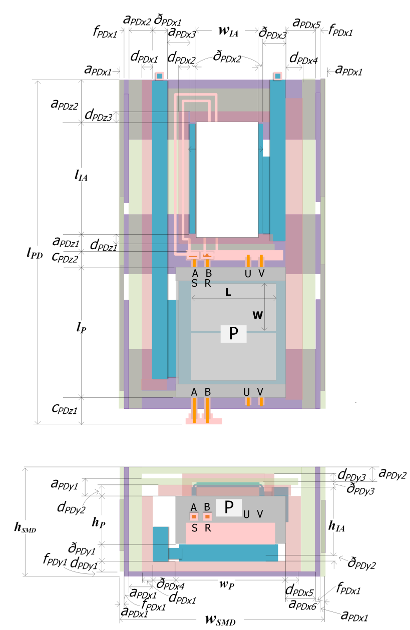
Virtual twin representations of the PEBB/NiPEBB active LRUs listed in Table IV are inputs to the VPP, along with x_V and r_V. The virtual twin model structure and corresponding parameters and constraints, k_U and r_U, respectively, are derived from actual physical twin measurements mapped to model structures defining PEBB/NiPEBB electro-thermal-physical behavior in the Power Train context. The physical twins represent published and (and associated reported work) described in Table II. In this way, actual measured data on active LRU hardware is the traceable authoritative source of truth for the VPP outcomes. The VPP produces Power Train PEPDS Drawers solution sets on the Pareto-front *for each unique set of power conversion stage design space variables, $x_S \subseteq x_V$, constrained by $r_S \subseteq r_V$*. The Drawers, described in Table III, in most cases, consist of an active LRU along with thermal management and basic or reinforced insulation creepage and clearance spacings resulting from an insulation coordination process [32]. They may also contain passive LRUs, as dictated by the needs of the associated power conversion stage and its controls. Drawer-level constraints, r_V, include maximum width-height-length constraints, minimization of Drawer dead-space, and maintaining the pressure drops, Δp_u, of individual active and passive LRU heat sinks presenting $\Delta p(T_A, \text{mfr})$ at the point of NiPEC thermal management system connection to the PEPDS Drawer.

Referring to Fig. 7 and 8, Drawer fitness functions utilize computationally efficient analytical electro-thermal-physical models executed within the VPP's evolutionary optimization environment to produce a performance space of competing objectives. These objectives, O_V, are derived from PEPDS building block KPPs listed in Table I, such as power density (ρ, MW/m^3), specific power (γ, kW/kg), and efficiency (η, %). The electro-thermal modeling is comprised of surrogate models derived from an upstream VPP on the range cooling solutions, which was a useful approach to obtaining a single thermal interface per Drawer for Drawers having multiple internal coldplates. This approach will be described in later work.

The VPP first ensures that active LRUs, arranged in Drawers described in Table III, and the conversion stages, are fully utilized given thermal constraints (i.e., $T_{j,\max} \subseteq x_S$). This is accomplished by searching for a $P_{\text{oi}}(T_A, \text{mfr})$ and an optimal heat sink design that maintains active LRU power semiconductors at their maximum junction temperature for every combination of $T_A \wedge \text{mfr} \in x_V$, through the use of a Non-dominated Sorting Genetic Algorithm (NSGA-II) [33]. The intent is to produce Pareto-optimized designs for every combination of x_V required to populate Power Train exploration space at the NiPEC level. The Drawer-level NSGA-II exploration space (the genes) includes magnetic component, switching frequency, etc. Because of the many unknowns of the NiPEC-based PEPDS, the intention is to proceed according to the process shown in Fig. 7 by implementing a range of Power Train solutions for each possible Power Train within a ship-wide PEPDS, according to the design space variables represented in Table V. This will include exploring the range of LRU heat sinking approaches [31] and connecting the



(a) SMD for FB-MMC. ac-dc converter in MVac/PG to MVac/PM Power Train.



(b) PD for MMC. dc-ac converter (VFD) in MVac/PG to MVac/PM Power Train.

Fig. 8: Physical compilation of Drawers

TABLE V: List of design space variables and specific x_V for Power Train example of Section III

Symbol	Description	Range	MVac/PG to MVdc	MVdc to MVac/PM
$v_{dc} \in x_S$	MVdc Bus Voltage	6…24kV	12kV	12kV
$f_e \in x_S$	Nominal Frequency	60, 120, 180, 240 Hz	60	60
$M_{\eth} \in x_V$	Cooling Approach †	FA-HS, D-CP, I-CP, DI-CP, D-2ϕ, I-2ϕ, D-VC, I-VC	I-CP	I-CP
$T_A \in x_V$	Coolant Temperature	5°C…40°C	15°C…35°C	15°C…35°C
$mfr \in x_V$	Coolant mass flow rate	0.02…0.1 kg/s	0.02…0.08 kg/s	0.02…0.08 kg/s
$M_T \in x_V$	Converter Topology ‡	MMC, FB-MMC, CFB, ISOS-DAB, ISOP-DAB, ISOS-CLLC, ISOP-CLLC, CF-MDAB, VF-MDAB	FB-MMC	MMC
$M_c \in x_V$	Converter Control Approach ⋆	PWM, PDM, ZCM-PDM, CA-PWM, CL-PWM, SCC	CA-PWM	SCC
$U_P \in x_V$	Active LRU type	P1000, P6000, HB-P6000, iP, DCx, OB	P6000	P6000

† Cooling Approach [31]: FA-HS (Forced Air Finned or Pin-Finned Heatsink), D-CP (Direct Coldplate), I-CP (Indirect Coldplate), DI-CP (Dry Interface Coldplate), D-2ϕ (Direct 2-phase), I-2ϕ (Indirect 2-phase), D-VC (Direct Vapor Chamber), I-VC (Indirect Vapor Champer)

‡ Converter Topology: MMC (Modular Multi-level), FB-MMC (Modular Multi-level with Full-Bridge sub-modules), CFB (Cascaded Full-Bridge converter Dual Active Bridge (DAB)), ISOP-MDAB (Input Series Output Parallel DAB), ISOS-DAB (Input Series Output Series DAB), ISOP-CCLC, ISOS-CLLC, CF-MDAB (Current-Fed Modular DAB), VF-MDAB (Voltage-Fed MDAB)

⋆ Control Approach: PWM (Pulse Width Modulation), Pulse Density Modulation (PDM), Zero Common Mode PDM (ZCM-PDM), Current Arresting PWM (CA-PWM), Current Limiting PWM (CL-PWM), Single Cycle Control (SCC).

resultant P_{oi} (T_A,mfr) to thermal management approaches within the NiPEC.

A use-case is considered for the MVac/PG to MVac/PM Power Train and the specific design space variables are provided in Table V. Referring to Fig. 5, because the MVac/PG to MVdc stage feeds a common MVdc bus, a Current Arresting PWM (CA-PWM) controlled Full Bridge Modular Multi-level Converter (FB-MMC) is applied to enable breaker-less protection because, under both MVac- and MVdc-side short circuit fault conditions the FB-MMC is voltage blocking. As a result, CA-PWM controlled FB-MMC can stop discharge of MMC sub-module capacitors whenever a short-circuit fault occurs [34]. This topology requires an sufficient sub-module capacitance and arm inductance, distributed among the SMDs, as sub-module inductance, which significantly exceeds the PEBB-level sub-module capacitance and inductance. The MVdc-MVac conversion stage is part of a VFD utilizes Single Cycle Control (SCC) [15] to need for high sub-module capacitance. These MMC sub-modules are configured into a PEBB Drawer (PD in Table III) with only distributed arm inductance, which is performance-constrained according to switching frequency and $T_A \wedge m_{\mathbf{fr}} \wedge V_{\mathbf{DC}} \wedge f_e \wedge U_P \in x_V$. Additional work is required to truly understand the trade space between sub-module capacitance and inductance versus the performance requirements (over the entire operational range) for both the SMD and PD cases presented. However, the results of this paper represent conservative results (verified by simulations) operating at P_{oi} (T_A,mfr).

Fig. 8a shows the compilation of SMD outside dimensions ($w_{\mathbf{SMD}}$, $h_{\mathbf{SMD}}$, $l_{\mathbf{SMD}}$) with these allocations placed around the PEBB **(P)**, capacitor bank **(CB)**, and inductor assembly **(IA)** LRUs. Fig. 8b shows the compilation of PD outside dimensions ($w_{\mathbf{PD}}$, $h_{\mathbf{PD}}$, $l_{\mathbf{PD}}$) with these allocations placed around the PEBB **(P)** and inductor assembly **(IA)** LRUs. During compilation, the VPP accounts for dimensional and mass impacts on PEPDS building block design and construction practicalities through cuboid allocations in xyz space around the Drawer LRUs. These Drawer-level allocations are assigned to the following functionalities (indicated in the dimensions of Fig.s 8a and 8b: (1) maintenance and shock & vibration travel space ($a_{\mathbf{PD}}$, green), (2) basic or reinforced insulation clearances ($d_{\mathbf{PD}}$, pink), (3) thermal management ($\eth_{PD}$, blue), frame structure and enclosures (f_{PD}, purple), and busses and bus-interconnects (c_{PD}, orange).

The thermal management approach impacts the P_{oi} versus KPP behavior in various ways. For example, for the MVac/PG to MVac/PM Power Train use case, an indirect water-cooled coldplate (I-CP) heat sink solution is selected. For the PEBB this means that power semiconductor modules are mounted on the coldplate surface. The sub-module inductor has coldplates mounted on two coil and two core surfaces. All codlpates are mounted through high thermal conductivity interfaces. This approach can ensure predictable sink temperatures on all I-CP cooled surfaces. It will be necessary for the coldplate coolant water to be de-ionized so that they can float with respect to ground (and for coldplate material to be stainless steel to avoid corrosion). Galvanic coldplate isolation between the LRUs and Drawer chassis is necessary because the mismatch between the functional insulation corresponding to the PEBB voltage rating and the terminal to ground voltage offset applied to any PEBB terminal (depending upon switching state) when PEBBs are connected in series to accommodate a MVdc bus voltage, v_{dc}. The MVdc bus voltage imposes a basic or reinforced insulation clearance distance separation between the coldplate

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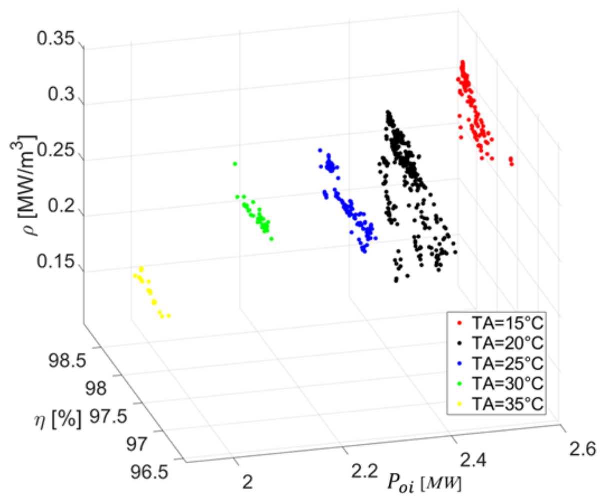

Fig. 9: MOPs produced by VPP of the PEPDS power train from MVac (generator input) to MVac (variable frequency propulsion motor output) at mfr=0.06 kg/s

and Drawer chassis, and it must also be assured that the coolant does not bring the coldplate itself to ground potential. Insulation clearance stand-offs are added at the Drawer level [32].The space impacts of insulation clearance are are shown by the pink space allocations in Fig. 8

Fig. 9 shows the VPP outcomes for the specific MVac/PG to MVac/PM Power Train use case described in the previous section. This result clearly shows clusters of designs as a function of one change in design space variable, inlet coolant temperate (T_A), provided to each SMD and PD, with mfr of 0.06 kg/s. The results of Table VI provide the first experiential basis for KPP goal/objective values for ρ and the exploration range for P_{oi}. These results show that the highest achievable P_{oi} is 2.589 MW, with ρ of 0.267 MW/m^3, for T_A=15°C and mfr=0.06 kg/s. The highest power density is $\rho = 0.353\,\mathrm{MW/m}^3$, with a resulting $P_{oi} = 2.54\,textMW/m$ for T_A=15°C and mfr=0.06 kg/s. These x_V conditions require chilled water freshwater coolant and, assuming de-ionization adds a for T_A=10°C temperature rise, represents the lowest possible continuous inlet water temperature point given the design space variable range T_A=10°C (per Table V). These results have an associated $\Delta p(T_A, mfr)$, which can be utilized assess impacts on the NiPEC-level thermal management system TPMs in follow-on work.

2) Navy integrated Power and Energy Corridor Design: Fig. 7 shows the linkage between the VPP and NiPEC through metamodel representation of PEPDS building blocks. Each point in the VPP Pareto performance space represents a single design. Data describing the design decisions made by the NSGA-II are extractable from these points. Referring to Fig. 7, metamodels are extracted from Pareto-front designs that are scaleable with x_V and traceable to the PEBB/NiPEBB inputs to the VPP at a time-stamped TRL. Variations in design can be selected according to an optimizing objective, O_V, such as *'the most power dense'* or *'the most efficient'*. *'The highest intrinsic power'* solutions may also be selected. These selections are

TABLE VI: KPPs vs. x_V

x_V		Power Density (ρ, MW/m^3)		Intrinsic Power (P_{oi}, MW)	
mfr (kg/s)	**T$_A$ (°C)**	**Highest P_{oi}**	**Most Power Dense**	**Highest P_{oi}**	**Most Power Dense**
0.02	35	0.151	**0.186**	1.385	**1.341**
	30	0.112	0.154	1.540	1.500
	25	0.168	0.182	1.568	1.553
	20	0.111	**0.231**	1.698	**1.598**
	15	0.189	0.221	1.726	1.689
0.04	35	0.213	0.253	1.830	1.774
	30	0.197	**0.249**	2.237	**1.886**
	25	0.150	0.251	2.153	2.006
	20	0.215	**0.305**	2.237	**2.047**
	15	0.164	**0.284**	2.376	**2.150**
0.06	35	0.205	0.223	1.916	1.914
	30	0.220	0.283	2.181	2.121
	25	0.248	0.294	2.323	2.26
	20	0.184	**0.319**	2.525	**2.398**
	15	0.267	**0.353**	2.589	**2.540**

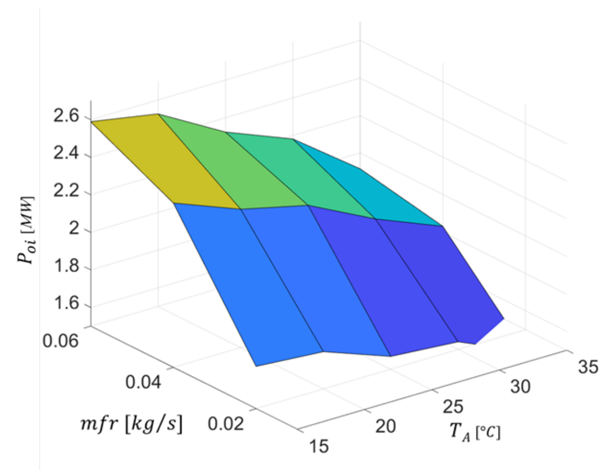

Fig. 10: P_{oi} as a function of *mfr* and T_A

made according to where they lie between KPP goal/objective and threshold levels. These FOCUS-compliant models are promoted as code-sets into the S3D CE environment for solution space exploration against NiPEC-level constraints, r_S, for SWAaP-C execution and subsequent ship-level SBD and AEF activities (see Fig. 4 and Table IV). Drawer metamodels represent the PEPDS building blocks configured into the power conversion functions within the Power Train, providing information on the number of Drawers, their dimensions and weight, and conversion stage-level P_{oi}, all as a function of x_V.

The necessity for the link between the PEPDS building block KPPs and the NiPEC TPMs, shown in Fig. 2, is demonstrated by the sample NiPEC segments containing PEPDS Power Train SMDs and PDs, as shown in Fig. 11 and 12, respectively. It is important to match the SMD selection from the results of Table VI to the use-case 4.57 MW PG rated supply power (P_s), corresponding to the orange reserved space in Fig. 6 and the PD selection to the use-case 19MW PM rated

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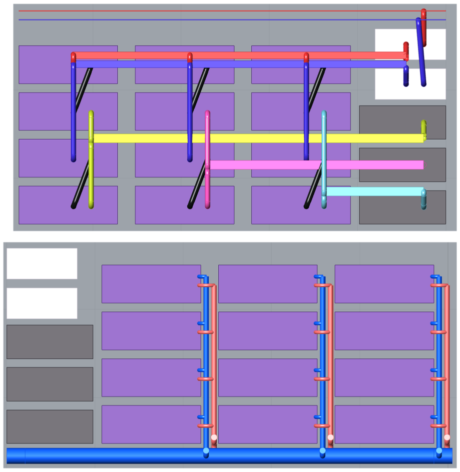

Fig. 11: NiPEC segment showing 12 SMDs (purple), 2 DCNs (white), and 3 ac_SW's (grey). *top*: electrical connections showing MVdc bus DC+ (blue) and DC- (red) connections and bus bars and MVac/PG 3-phase connections (yellow, magenta, cyan). Note DC main bus bars running the full length of the segment at the top. *bottom*: cooling water connections showing supply (blue) and return (red). Structural support omitted for clarity.

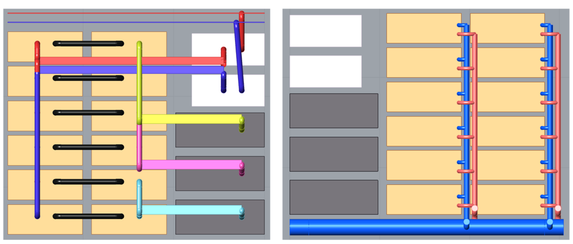

Fig. 12: NiPEC segment showing 12 PDs (orange), 2 DCNs (white), and 3 ac_SW's (grey). *left*: electrical connections showing MVdc bus DC+ (blue) and DC- (red) connections and bus bars and MVac/PM 3-phase connections (yellow, magenta, cyan). *right*: cooling water connections showing supply (blue) and return (red). Structural support omitted for clarity.

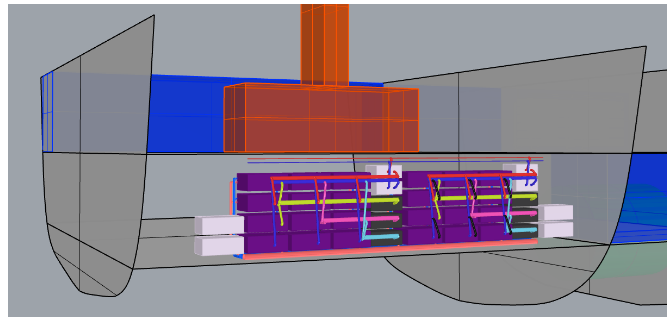

Fig. 13: NiPEC segments for the generator shown within the engine room of the notional ship. This represents the first half of the example power train.

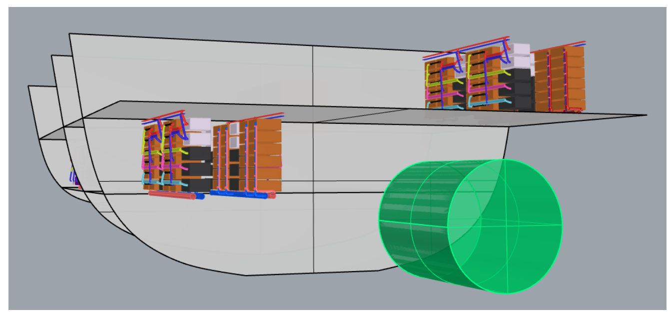

Fig. 14: NiPEC segments for the propulsion motor shown within the motor room of the notional ship. This represents the second half of the example power train. Note that parallel segments are required due to the short compartment length and the number of required PEBBs.

power (P_d). For v_{dc}=12kV. Analyzing the VPP performance space data for designs at the highest P_{oi} and most power dense corner cases, seven (7) of the most power dense designs in Table VI (corresponding to bolded P_{oi} and ρ values) result in SMDs and PDs that are nearly identical design solution for all 7 sets of design space variable combinations. The selected SMD dimensions are 1.15 m (w) x 0.45 m (h) x 0.83 m (l). The selected PD dimensions are 0.83 m (w) x 0.33 m (h) x 0.86 m (l). The goal of S3D-based SWAaP-C is to arrange the required Drawers for all Power Trains in a way that minimizes NiPEC under-utilized space, while meeting zonal power delivery requirements, and matching outcomes with thermal management solution space exploration.

Revisiting the example use-case, a full power train was modeled using the most power-dense versions of the SMD and PD, developed using the VPP (see Table VI). It should be noted that although three distinct Power Train types are indicated in Fig. 5, the Drawers that are not highlighted represent parts of other Power Trains, fed from zones that are not shown. The number of SMDs and PDs were determined from the highest P_{oi} Power Train produced by the VPP. It is impossible to match the P_{oi} to the PG capability and the load demand. Therefore sufficient groupings of SMDs and PDs derived from Power Train power stages are populated to match power and energy transport capability with source(s) and load(s) with a given assumption of T_A and mfr. In this example, twenty-four (24) SMDs convert the generated three-phase power at 7kV (from the point of MVac/PG bus connection) into the MVdc bus voltage of 12kVdc, with six AC disconnects and four DCNs to allow for galvanic isolation during fault, isolation and recovery actions or during repair. This equipment is shown within the reserved space in the engine room of the ship in Fig. 13. In addition to the NiPEC segments containing the SMDs, there are also four DCNs shown which provide isolation for the main bus within the watertight compartment.

Similarly, forty-eight (48) PDs are required to convert the MVdc distribution voltage to point of MVac/PM load supply. This equipment is shown within the reserved space in the motor room of the ship in Fig. 14. The power corridor in this example must be arranged in parallel sections due to the short compartment length and the large number of PDs required.

The total volume required by the 24 SMDs and their associated disconnect switches, electrical connections, cooling

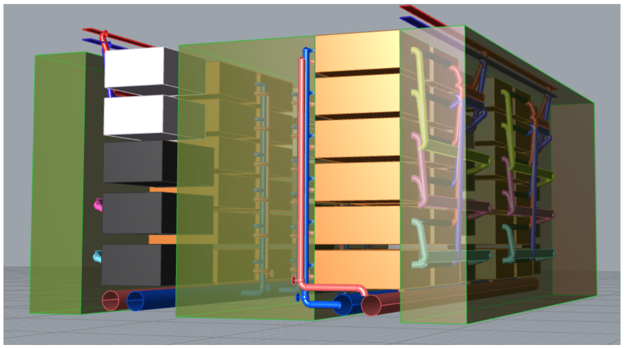

Fig. 15: Parallel NiPEC sections with access space highlighted in green. Access space between the two corridor segments is overlapping, allowing racking of Drawers from either side.

water piping and structural support is 23.99 m^3. The total volume including access area for operations and maintenance is 68.10 m^3. Per [35], the minimum machinery space working clearance width allowance is 0.584 m; this clearance provided on either side of the NiPEC equipment. Space for removal of a Drawer, equal to the full depth of the Drawer, is added to the working clearance at the front of the NiPEC segments (in the direction the Drawers would be removed).

The total volume required by the 48 PDs and their associated disconnect switches, electrical connections, cooling water piping and structural support is 57.98 m^3. The total volume including access area for operations and maintenance is 130.31 m^3. The access areas for Drawer removal on the parallel sections facing one another are permitted to overlap, thus reducing the overall volume and footprint required. See Fig. 15.

Close-up views of PD-based and the SMD-based NiPEC power stages (each one-half of a Power Train), and their associated corridor segments, are shown in Fig. 11 and 12 along with required electrical connections and cooling water piping. Note that the PDs present a more power-dense arrangement due to their smaller height, allowing six PEBBs per stack. These segments are repeated as necessary to match source/load (S/L) to $P_{oi}(T_A, mfr)$.

IV. Analysis of Results

In an attempt to begin to quantify the threshold levels of KPPs and TPMs, Table VII provides the MOPs associated with the NiPEC installations of PEPDS described in the previous section. These results correlate to the KPP vs. x_V results of Table VI. Seven (7) conditions, which will define the installed power density (ρ_i) and the power stage power density (ρ_{ps}) of the respective MVac/PG and MVac/PM interfacing NiPEC segments, use a selected SMD and selected PD for system building from the underlying data correlating to the bolded KPPs in Table VI, as described above. An analysis of Table VII will lend understanding to the capability that can be achieved by the installation of PEPDS into NiPEC segments and the limitations of that capability given the constraints on the upstream thermal management system.

The goal is, firstly, to match the installation of PEPDS equipment to the S/L in its respective zone with its

TABLE VII: PEPDS MOPs vs. NiPEC TPMs

Function			PEPDS KPPs (MW/m^3)		NiPEC-PEPDS TPMs	
S/L	**mfr (kg/s), T$_A$ (°C)**	$P_{s/d}$ (MW)	ρ_i	ρ_{ps}	**Space Claim** (m^3)	ρ (MW/m^3)
PG	0.02, 35	4.48	0.29	0.25	47.98	0.10
	0.04, 30	4.48	0.39	0.31	35.99	0.13
	0.06, 20	4.48	0.51	0.48	23.99	0.19
	0.04, 20	4.47	0.50	0.37	35.99	0.13
	0.02, 20	4.47	0.36	0.35	35.99	0.13
	0.06, 15	4.48	0.55	0.50	23.99	0.19
	0.04, 15	4.48	0.44	0.31	35.99	0.13
PM	0.02, 35	10	0.52	0.49	57.98	0.17
	0.04, 30	14	0.69	0.63	57.98	0.24
	0.06, 20	19	0.85	0.85	57.98	0.33
	0.04, 20	15	0.78	0.73	57.98	0.26
	0.02, 20	13	0.63	0.63	57.98	0.22
	0.06, 15	19	0.97	0.91	57.98	0.33
	0.04, 15	17	0.79	0.78	57.98	0.29

$P_{oi}(T_A, mfr)$ capability to achieve the layout of Fig. 5. If this can be done for PG, then the power supplied (P_s) can be provided through the MVac/PG to MVdc power stage utilizing the NiPEC space on only one side of the ship, leaving room for NiPEC-PEPDS service through other power trains utilizing the empty NiPEC segment space on the opposite side of the ship (Fig. 13). The corresponding space claim will be what was stated in the previous section (23.99 m^3). Referring to Table VII This can be only be accomplished for two conditions, mfr=0.06 kg/s with T_A=15°C and 20°C.

If the same can be done for the PM, then the full power demanded by the propulsion system (P_d), under its 19MW nominal condition, can be supplied by the PD-based installation of the MVdc to MVac/PM power stage in the associated NiPEC segments on both sides of the ship (Fig. 14), within corresponding space claim constraint (57.98 m^3). Otherwise P_d must be limited to avoid overloading the PEPDS equipment. Referring to Table VII, this is only achievable for the same conditions described for the minimum space claim case of Fig. 13.

V. Conclusions

There is an increasing need to understand the true impact, or "value proposition" of power electronics-based systems at the system level, not only for shipboard electrification but for a wide range of applications [36]. Thus paper has presented a unique integration framework (Fig. 4) that connects MBSE to early naval ship design exploration using an evolutionary environment to produce performance space vs. design space for PEPDS building blocks and SBD to identify feasible and viable implementations within power and energy corridors (NiPEC). The ultimate goal is to define various measures of "goodness" by establishing thresholds and goals for them, and creating a coherent chain of evidence from the system and other models used in a program.

The contribution so far, is to demonstrate two critical steps within the Integration Framework, VPP and SWAaP-C (see Table IV and Fig. 7, through one notional use-case that for the Power Trains associated with the integration of generation and propulsion with NiPEC-PEPDS. The analysis of the results of this use-case are not conclusive, but they demonstrate, in part, the process of obtaining valid parameter goal/objective and threshold values for MOPs (associated with power and size reduction vs. coolant surface areas) while applying practical design considerations and ensuring that PEPDS building blocks promoted to NiPEC level exploration are solutions on the Pareto-front of an evolutionary design process outcomes. The proposal has high "face" credibility, *which further research aims to confirm as a practical general approach*.

Future work will apply the same methodology demonstrated in this paper to produce PEPDS Power Trains solutions, and the MOPs, required for every path between ship-wide PGs, DES's, PMs, MLs and SSLs (e.g. Fig. **??**) and then, as part of NiPEC solution space exploration, match associated Power Train $P_{oi}(x_V)$ to to NiPEC-PEPDS TPMs, such as Space Claim, zone by zone. It will be necessary to perform a full ship design, using information from the LEAPS repository, to determine the limits of NiPEC space availability, which will define the NiPEC threshold requirements. The corresponding KPPs resulting from this process establish a starting point for subsequent SBD activities through use of yet-to-be developed, transferable metamodels between VPP (an offline process) and SBB. These metamodels will rely heavily upon the concept of surrogate models . Once the range of KPP threshold values are identified (as well reasonable goal/objective stretch values as a function of technology insertion) then the process can be automated in RSDE, as indicated in Fig. 7, determine feasible sets of NiPEC-PEPDS design solutions, by matching its installed power capability (as a function of design space) to the S/L requirements of the ship platform. This will form the bases of follow-on activities, within the integration framework described by Fig. 4 and Table IV to determine the "best" solutions, eventually leading to an identification of the most viable solutions based upon a weighting of stakeholder needs.

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