Modular Integrated Power Corridor

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Abstract—**The modular, integrated power corridor design for ships creates a cost-effective but robust method of meeting the intensive needs of the warship of the future. The power corridor described in this paper integrates the functionality of power transfer, conversion, isolation and storage in individual modules that are fabricated off-hull and easily integrated shipboard. The individual building modules are consistent with one another and have standardized functionality, hardware and control interfaces. This modularity, standardization and off-hull construction combined should significantly reduce both construction and life-cycle costs. The final product of his paper is a detailed model of a sample power corridor arrangement.**

Keywords*—*power distribution, modularity, ship design, MVDC

I. BACKGROUND

At the turn of the century the Electric Ship Design Research Consortium (ESRDC) was created to help the US Navy with one of its next major technical challenges, namely advances in the technology, expertise and design to support the all-electric surface combatant of the future and its attendant high-power and pulsed electrical weapon and sensor systems. The authors of this paper are members of the ESRDC team, and for the past five or so years, have been working on the design of the power train of the next all-electric combatant. They introduced and championed the concepts of Power Corridor and Reserved Space. As a consequence the design of the power train of the all-electric ship can now be considered much earlier in the design cycle when design changes are easier to make and much more cost effective. This enhances the quality of the resulting design because it encourages the designer to consider the power train as a system and optimize its overall performance rather than optimizing selected elements of it in a vacuum. The results of this initial study are included in [1] and show that the concept of reserved space produces useful design results.

The power corridor incorporates in a single entity the distribution, conversion, isolation and storage of main bus power throughout the ship. This power corridor concept introduces advantages in cost, survivability, and arrangement:

Cost. All modules of the power corridor are designed for off-hull construction and easy assembly onboard; with installation essentially involving rigging, bolting and connection. This reduces costs of initial construction and repair and modernization. In addition, the modules can be built and tested in a clean factory environment with ease of access, which should reduce cost and improve reliability. In addition, the power conversion elements of the power corridor, titled Power Electronics Building Blocks (PEBBs), are identical, modularized components that can provide ac-ac, ac-dc, dc-ac, or dc-dc conversion; thus, the ship will contain hundreds of identical pieces of hardware rather than many bespoke units. This redundancy reduces costs in production, installation, supply chain support and training.

Survivability. At the most basic, survivability guidelines recommend providing redundant functionality that is geographically separated and supporting functionality that is colocated geographically. The second dictate is met by the power corridors co-location of the distribution, conversion, isolation and storage functions. The first dictate is met by separating multiple redundant power corridors vertically and horizontally in the ship. Further, the identical PEBB units are designed to be portable and easily replaceable, so that the PEBBs can be replaced shipboard by the crew if they are damaged but surrounding equipment is still viable.

Arrangement. The reserved space concept sets aside a location for the power corridor in the very earliest stages of design. Since the power corridor contains so much functionality, this unit included early in the design simplifies the process of locating individual units for each function. The uniformity of the modules also aids in the arrangement process.

This paper provides a detailed description of the elements of the power corridor in Section 3, with an introductory description of the notional design case in Section 2 and a summary and conclusions in Section 4.

II. DESIGN CASE

As a design case, the authors used a notional destroyer-sized vessel with a representative set of payload equipment and power generation equipment. The owner specifications of this initial study were that the ship should not exceed 10,000 metric tons in displacement and should provide 100 MW in installed power with the distribution bus voltage set at +/- 10,000 Volts dc. The installed weapons systems include Active Denial System, Laser, Vertical Launch System and Railgun for a total power requirement of 19.8 MW. The sensors included in our original study are Integrated Topside Array, Hull-Mounted Sonar, Towed-Array Sonar, and S- and X-band Radar arrays, for a total power requirement of 9.5 MW. All loads not individually modeled were aggregated to vital (12.6

This material is based upon research supported by, or in part by, the U. S. Office of Naval Research (ONR) under award number ONR N00014-14-1-0166 ESRDC Designing and Powering the Future Fleet; N00014-16-1-2945 Incorporating Distributed Systems in Early-Stage Set-Based Design of Navy Ships; ONR N00014-16-1-2956 Electric Ship Research and Development Consortium; and by the National Oceanic and Atmospheric Administration (NOAA) under Grant Number NA14OAR4170077 - MIT Sea Grant College Program.

MW) and non-vital (0.14 MW) loads. For more details about the ship design and the loads, please see [2].

The current owner requirements for the 2017 study are similar to the original 2012 study but they differ in two essential elements. The first difference is that the bus voltage was reduced from 20,000 VDC (+/- 10,000 V) to 12,000 VDC (+/- 6,000 V). The original study [1] suggests that even though the reduction in bus voltage makes the system bigger, the magnitude of the increase is small enough to be easily absorbed in the overall ship design. As it happens, by lowering the bus voltage to +/- 6,000 V we bring it to within the current state of the art of marine bus technology and therefore make the risk of experimenting with high voltage technology a reasonable proposition. The second owner requirement that is changed from the original is that the maximum installed power was reduced from 100 MW to 80 MW. The reason behind this decrease is that the present list of loads can be accommodated with 80 MW of supplied power, a carefully monitored overloading of the power train, appropriate energy storage, and a suitable speed management. We assume two main engines of 36 MW each and two auxiliary engines of 4 MW each.

To meet this revised design case, we propose four power corridors, each nominally rated at 20 MW with a 20

III. COMPONENT DESIGNS

In this paper the authors focus on defining the different elements of the power corridor so they can be fabricated off-hull and easily integrated shipboard. An overview of the power corridor elements can be seen in Figure 1. The major components that are considered include:

- Bus cable and conduit (magenta)
- Power converter stack (dark blue and brown)
- Interface junction box (orange)
- Energy storage (salmon)
- Circuit breaker or disconnect (teal)
- Bulkhead penetration (gray)

A summary of the key dimensions of the space occupied by the power corridor is given here for convenience. The details can be found in [2]. The height between decks below the main deck varies between 2.6m (102 inches) and 3.1m (122 inches). The depth of the regular stiffener is assumed to be less than 5 inches and the depth of a deep stiffener and of girders to be less than 12 inches. Figure 2, not to scale, shows the positioning of a power corridor relative to the stiffeners and girders: the dark blue rectangle represents a cross-section of the power corridor, the smaller t-shapes are the stiffeners and the larger t-shapes are girders. For this study we assume that the lateral and longitudinal placement of the power corridor on each deck can be made at or near the desired position as long as the height of the power corridor is 97 inches or less, which equals the overall height of the space (102 inches) minus the depth of the stiffener (5 inches). The longitudinal extent of the power corridor is from bulkhead 3 to bulkhead 10, extending over eight watertight subdivisions, and thus penetrating into every electrical zone [2]. There are two characteristic compartment lengths between bulkhead 3 and 10 and these are order of 16m for the engine rooms and 8m elsewhere. Fortunately, the modular nature of our power corridor is sufficiently flexible to accommodate the small differences between the actual and assumed compartment lengths.

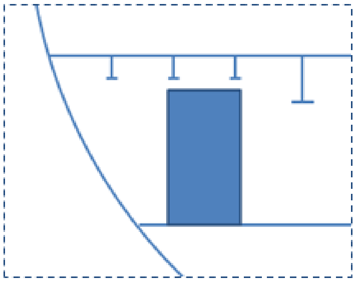

Fig. 2: Sample power corridor and stiffener positioning; not to scale.

IV. POWER CORRIDOR COMPONENT DESIGN

The modular integrated power corridor design adopted in this paper is heavily influenced by the power converter design proposed in [3]. The following subsections describe each individual modular component of the power corridor.

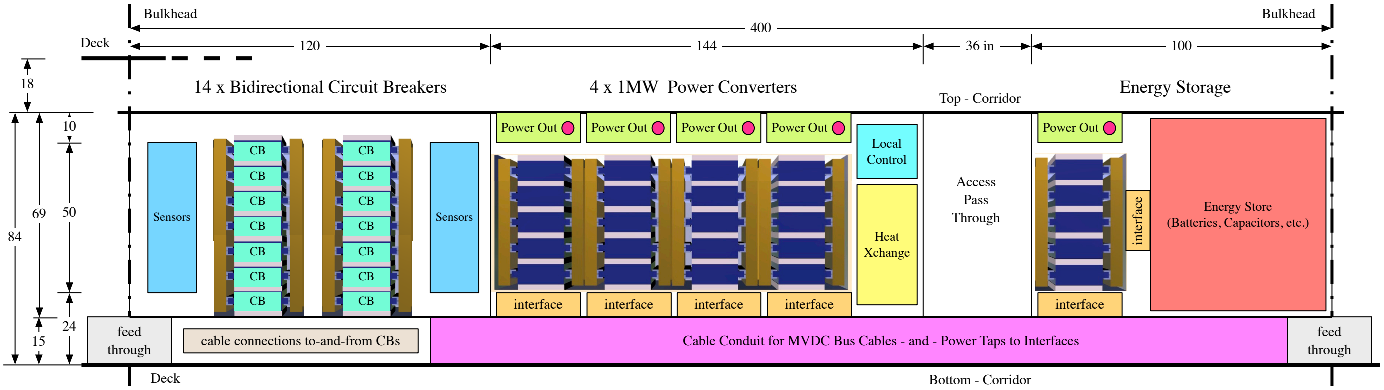

Fig. 1: Modular integrated power corridor

A. *Bus cable and conduit*

In the previous design reported in reference [1], we self-imposed a limit of 500A per individual bus cable as a reasonably high ampacity within the state of the art for marine applications. Cable runs that exceeded 500A were serviced by multiple pairs of cables. In the present paper we investigate the effects of lowering the value of the bus current per cable; namely, we lower the bus current to a quarter of the original value, or 125 A. At 12 kVdc, each 125 A bus line is capable of handling 1.5 MW of power, so we need 54 pairs of cables to transmit the entire 80 MW of power we can generate under the assumption that no overloading is permitted. A 20% margin would require transmission of 96 MW of power, necessitating 64 cable pairs. One possible arrangement is to group the bus cables into four corridors, each nominally 20 MW. To be exact, each corridor can carry 21 MW of power using fourteen pairs of 1.5 MW cables and has additional space for two spare 1.5 MW cable pairs; the cable pair arrangement can be seen in Figure 3.

The bus cable conduit is a rectangular cylinder resting on the one of the inner decks. The cross section measures 15 inches high and 30 inches wide. The principal purpose of the conduit is to house the bus cables. For our study each corridor contains 14 pairs of cables and space for 2 spare cable pairs, assuming a one inch cable diameter and one inch horizontal spacing between cables in a pair, with greater spacing around pairs. For details see Figure 3.

B. *Power converter*

The PEBB modular power converters, introduced by Ericsen [3], are universal converters that provide ac/dc, ac/ac, dc/ac or dc/dc conversion at various voltages, and can be operated in a uni- or bi-directional manner. This single common unit is of a size and weight that can be carried through the ship and easily racked out and replaced by the ships crew while underway. According to recent literature, substantial progress at achieving operational PEBBs has been made and commercial releases are not too distant in the future; see, e.g., [4].

For the purposes of this study, we assume the following: Each of the PEBB units operates with dc and/or ac settable voltage values and waveforms within the design specification limits. The power rating is set at 200 kW per module. Electrical input and output connections are on two opposite vertical faces. Each module is inserted into a cabinet such that water-cooled plates for thermal management make contact above and below the unit and electrical connections are to the left and right, as seen in Figure 1.

The connections running between the distribution bus and the individual PEBB units are located in the conduit on the left-hand side of the cabinet and connect to the distribution bus cable at the bottom of the PEBB stack via an interface junction box, located between 15 and 24 inches above the deck. The connections between the PEBB units and either the serviced loads or the power generation modules are located in the conduit on the right-hand side of the cabinet and connect to the cables leading to the loads or from the generators at the top of the cabinet via another interface junction box, located at 70 inches above the deck. These cabinet conduits are shown in brown in Figure 1.

A cabinet with five vertically-stacked PEBB modules measures 46 inches high, 30 inches deep, and 30 inches long. Although the length of each block used in this study is 30 inches, longer blocks can be easily accommodated if the final dimensions of the individual PEBB units exceed this length since almost the entire length of the compartment is available.

Identical PEBB stacks provide the functionality of rectifiers between the ac power generation modules and the dc distribution bus, step-down transformers between the distribution bus and lower-voltage dc loads, inverters between the distribution bus and ac loads, and bi-directional converters between the distribution bus and the energy storage modules.

C. *Interface junction box*

An interface junction box provides the connectivity between the bus cable and the PEBB stacks. As shown in Figure 1, the connections to the individual bus cables lay within the conduit below 15 inches above the deck level. The junction box occupies the space between 15 and 19 inches. At 19 inches we stud connections that connect the cables from the PEBB stack. The connections between the interface module and the cables in the conduit are created during the factory production process; shipboard assembly merely requires connection of the PEBB stack cables to the studs on the interface module.

For this example, we assume that six of the 14 total pairs of cables in a conduit are powered by main engine number 1, six by main engine number 2, one by auxiliary engine number 1 and one by auxiliary engine number 2. Each standard interface module provides connection to two of the six cable pairs associated with each main engine and to the single cable pairs associated with each of the two auxiliary engines, thus enabling each converter stack to draw power from any of the generators. No-load disconnect switches allow us to connect to none, one or two cable pairs for each of the main engines and to none or one of the two auxiliaries; this connection is managed electronically via the control system. These disconnect switches provide two functions: they enable reconfiguration for optimal operational conditions and reconfiguration in the event of damage and the need to re-route power from different sources.

One interface unit is required for each stack of power converters as shown in Figure 1. As described earlier, a power converter stack is rated for 1.0 MW; therefore, each stack requires access to a single pair of cables.

Figure 4 shows an example connection scheme. The connection going up into the stack of 5 PEBB converters must be connected to one pair of cables in the conduit. The interface junction box provides switched connections to six of the fourteen cable pairs in the conduit; the control system closes one of the six no-load disconnects to allow connection to any of the four available generators on the fly as necessitated by the ship operational alignment. In this example figure, the PEBB stack is drawing power from main generator number 1. A sequence of three converter stacks (and three interface boxes) would provide connectivity to every cable pair in the conduit.

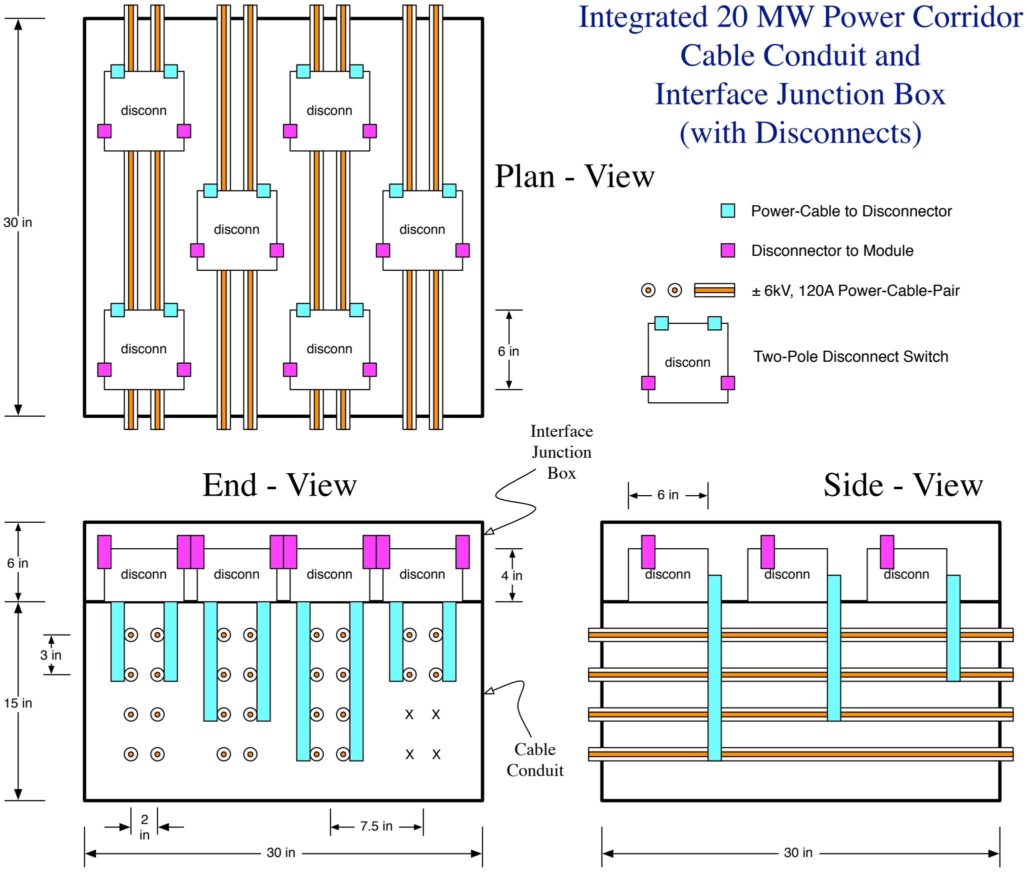

Fig. 3: Conduit interface

D. Energy storage

Locating energy storage components within the power corridor provides two important advantages. Firstly this energy storage is inherently distributed throughout the ship making it easily accessible to many possible loads. Secondly, it becomes controllable via the now standardized PEBB units that enable full control of power flow and direction in-to or out-from the storage elements. At this point it is not critical what type of device employed and may be one or several of various technologies including for example batteries, capacitors, flywheels and/or fuel cells.

The energy storage device is connected to the main distribution bus via a PEBB power-converter tower operating as a bi-directional device to charge and discharge the energy storage. Thus, if the energy storage unit is charging, power flows from the distribution bus through the PEBB and into the energy storage device; if the energy storage unit is discharging, power flows outward through the same PEBB stack to the distribution bus and from there to any load as required.

E. Circuit breaker

The MVDC circuit breakers are series-connected circuit elements in the MVDC bus and occur for protection and isolation at the zonal boundaries. At this point they are not off the shelf, partly because at present the necessary fault protection specifications are not yet determined, and partly because MVDC is a relatively new technology beyond specialized installations. Allowance for a substantial amount of space was provided to be conservative. The space allowed is slightly less than for the PEBB converters and is based upon an assumption that sustained peak breaking currents in the confined size of a ship will not be typical land-based values of over 50 kA but rather more manageable size of well under 10 kA.

For our design we have fourteen active cable pairs and space for two spare ones. Figure 1 shows the fourteen bi-directional circuit breakers (CB) needed for our design. In addition, at the top of each CB tower we have room to install circuit breakers for the two spare cables not included in Figure 3. Each CB has a cable on one side that is of sufficient length to connect to the bulkhead feed-through, and a cable on the other side to connect to the bus conduit. These cables are housed in the vertical conduits shown in brown in Figure 1. The actual cable connections are made up in the field, beginning at the bottom layer and continuing upwards. Access is from the top at the 15 inch level. This method of connectivity is feasible because our cable is thin (1/4 of an inch of copper). For thicker gage cables, we will experiment with alternate connectivity schemes and locations.

The design presented herein includes full circuit breaking capability at the junction between adjacent electrical zones. Since the electrical distribution system contains power elec-

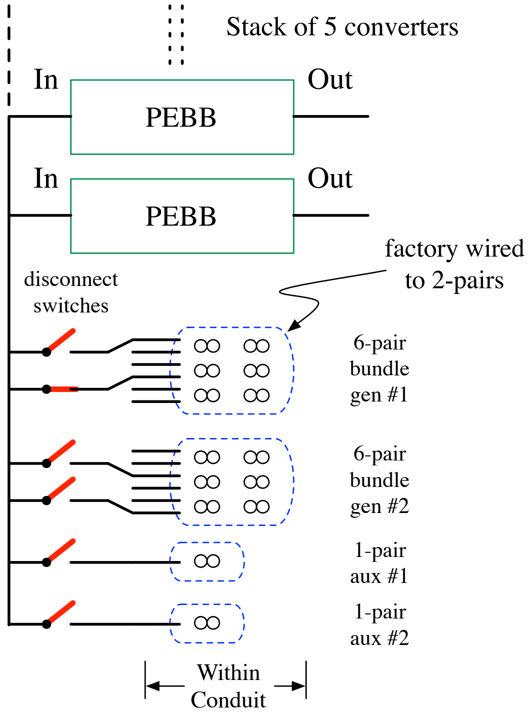

Fig. 4: Switch wiring between MVDC cables and PEBB converters.

tronics at key points throughout the system, it may be possible to control the flow of power using the power electronics and thus obviating the need for circuit breaker technology. In the example design, this would require securing power to an entire power corridor in order to isolate a section, although advances in switching and control technology may make this possible in an acceptably short timeframe. If this is the case, then the breakers in this design will be replaced with no-load disconnects, which will significantly reduce the size and weight of the components, thus returning some prime real estate for use by other power corridor functions.

F. Bulkhead penetration

Each bulkhead that is in the way of the bus conduit will have a cable penetration structure that is the size of the cross section of the bus conduit. In our case this is 15 by 30 inches. The actual opening might be a little bigger to allow easy operations in the field but it is not expected to exceed 23 by 38 inches. The cable penetration structure consists of a plate supporting 16 wall-feed-through bushings; the plate is welded into the bulkhead. The length of the bushing on each side of the bulkhead is 6 inches. There are two types of connections. The first one connects each bushing to the corresponding bus stud of the bus conduit, and the second connects the bushing to the cables emanating from the circuit breakers. The distance between the bushing and the connection is estimated to be 16 inches (about twice the bend radius of each individual cable). The actual connections are created on board the ship during construction, starting from the bottom row of bus cables. Access is from the top of the power conduit. This example illustrates the potential benefits of creating Navy-approved plug-in connections.

V. SUMMARY

The concept of introducing the Power Corridor as a design element for the all-electric warship design was very well received by the ESRDC design community. Encouraged by this result, our research team continued its earlier research to extend our concept to an integrated and then modular Power Corridor. By integrated we mean that all important elements of the all-electric power train are dealt with simultaneously and traded off with each other early in the design. Next by modular we mean that the overall system is made up of separable components that can be fabricated off the hull thus assuring improved quality by fabricating and testing important power elements in the controlled environment of a factory environment. Furthermore by carefully defining the interfaces we can increase the number of similar elements in the design thus decreasing the number of different objects we fabricate in each production run. This also simplifies the inventory we need for repairs.

By paying attention to the efficiency during fabrication our exercise identified a critical void in our knowledge basis. This void is the need of Navy-approved power-plugs at the low megawatt level. The availability of such power-plugs will simplify the deployment and versatility of our concept and thus reduce both fabrication and operational costs.

Additional future work includes examination of the connection to in-zone loads and generators, and detailed design of the cabinet for PEBBS to include the electrical, thermal and control elements.

The existence of an overall power train model will allow us to develop simulation models and evaluate different system metrics that compare and contrast different designs. An example of such a simulation model is the one that computes a vulnerability metric as proposed in [5]. Additional studies into dynamic loading and pulse loading would be interesting as well.

Our immediate goal in writing this paper is to present our results to the ESRDC design community so we can get their suggestions for improvement and thus establish a canonical power train design model.

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