# Design of a Power Corridor Distribution Network

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***Abstract*—In this paper, we develop an early-stage design tool to model the energy distribution system of an all-electric warship. The development of a design model is now possible because we have adopted the concept of space reservation in the form of integrated modular power corridors. Our initial study focuses only on a subsystem of the energy distribution system; namely, the shipboard electric bus, the load centers in the ship, and the converters needed to transform the bus power to the power needed by the load. Our design procedure starts by selecting the number of corridors (N where N $>$ 1), and dividing the ship's electric bus equally among the corridors. Our objective is to develop a balanced network of connections that can deliver full power between the generators and the loads using any of the N-1 corridors.**

***Keywords*—Power Distribution, Network, Ship Design.**

## I. Introduction

### A. Background

The power corridor is the space on board the ship designated to house elements of the power distribution system of an all-electric ship. The initial step [1] is to reserve space at the earliest stages of design for all relevant components of the system, co-located into power corridors. Reserving the space to place the multi-cable bus and the associated converters and sensors early in the design process makes it possible to develop a model to answer questions associated with the electric bus at any time during the design cycle, e.g. questions about cable maintenance, safety during operations, signatures, or modularity during fabrication.

The idea of a reserved-space corridor evolved to the concept of the integrated power and energy corridor [2], which incorporates into a single modular entity all the electrical distribution functions for the main bus power throughout the ship, including transmission, conversion, protection, isolation, control, and energy storage. In addition, the power corridor provides the services required to maintain and operate these components such as thermal management, structural support, ventilation and access. All electrical components of the ship with the exception of power generation and power usage (loads) are located within the power corridor. See, for example, Fig. 1. Multiple redundant power corridors are geographically distributed in the ship for robustness.

This material is based upon research supported by, or in part by, the U. S. Office of Naval Research (ONR) under award number 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; by the National Oceanic and Atmospheric Administration (NOAA) under Grant Number NA14OAR4170077 - MIT Sea Grant College Program; and by 'la Caixa' Fellowship under grant number LCF/BQ/AA17/11610007.

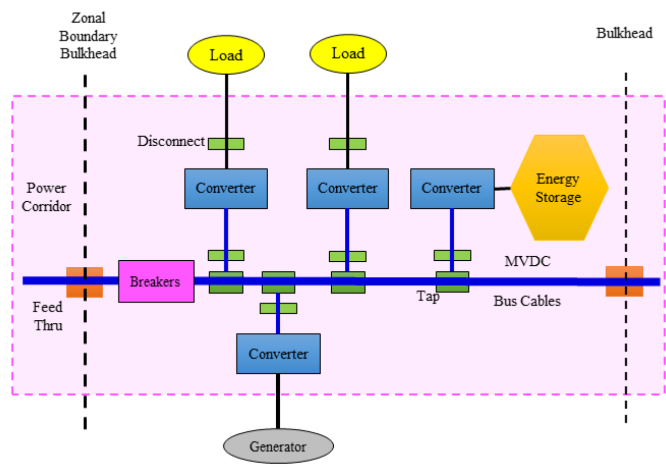


Fig. 1. Power corridor elements. All items within the shaded section are contained in the power corridor.

With this further definition of the power corridor concept we can now evaluate questions such as the effect of off-hull construction and survivability after damage in addition to the questions enumerated above. Future expansions in the power corridor concept include inclusion of thermal management, operational control and communications.

### B. Overview of the Network Design

The goal of this work is to develop the algorithms and the process necessary for designing the power corridor network, thus determining the number and size of the component units, the number and size of bus cables, and the connectivity between them to achieve a robust, resilient power distribution network.

Our current study focuses only on a subsystem of the energy distribution system consisting of the shipboard electric bus, the load centers in the ship, and the converters needed to transform the bus power to the power needed by the load. Our objective is to develop a balanced network of connections that can deliver full power between the bus and the converters under normal conditions and under the loss of any one full corridor. Once successfully tested, these tools are a candidate for inclusion in the Smart Ship Systems Design (S3D) environment [3].

One of the interesting aspects of power corridor we explore is the flexibility and redundancy allowed through the use of multi-cable electrical buses combined with modular converters constructed from Power Electronics Building Block (PEBB) units [4]. With this construction, it is not necessary to connect every bus cable to every converter and thus every load. As long as every source is connected to every bus cable, which we require, then as long as each load is connected to at least one cable, there is a path from every source to every load. One question then becomes determining which load should be connected to which cable.

Using the algorithms and process outlined in this paper, the designer is able to determine the power distribution along the length of the ship hull, determine the capacity of the individual power corridors, determine the number of PEBB units required, establish the connectivity between PEBB stacks, cables and loads, and balance the load across cables for improved performance. In the previous statement, a PEBB Stack is a fixed group of PEBB units as defined further below

As an example case, we use the algorithms to define a power corridor for the notional ship described in [5], which also defines the design requirements used in this study.

## II. Problem Statement and Constraints

The goal is to design a connected electrical power distribution network such that the system can operate at full power with no cable overloaded, either in normal alignment or with any one complete corridor disabled.

The problem is formulated by the following statements:

Given the following information:

1) The location of all major watertight subdivisions of the ship (decks and bulkheads).
2) The location of the electric zones of the ship. This allows the placement of circuit breakers at the zonal divisions.
3) The location and power requirement for each electrical load or load center in terms of power level, voltage and current type. Location can be specified to the granularity of watertight sections.
4) The location and power supplied by each electrical power generator, to include power level, voltage and current type.

The user must specify:

1) The number and location of the ship's power corridors. In our example, we have selected four corridors located port and starboard on decks 2 and 4.
2) The voltage and current type for the main bus. We selected 12 kVdc (± 6 kVdc).
3) The size and capacity of each main bus cable. We selected 1.5MW.

To determine:

1) The power level of each corridor, based on the transmission requirements due to the loads and generators.
2) The number of main bus cables in each corridor, based on the power level of the corridor, the capacity of the cables selected, and the design margin for extra cables.
3) The number and location of PEBB units, based on the load distribution within each watertight bulkhead section.
4) Which cables are connected to each aggregated load.

By varying:

1) Initial number of cable connections in each compartment to each cable for each corridor.
2) Connections available per PEBB stack. Varied through a scale factor vector (*Multipliers*) applied at the start of each analysis.

We additionally impose the following set of constraints:

1) The maximum carrying capacity of the ship's electric bus is equally divided among the corridors. The main bus capacity of each corridor is the same, and the corridors all have the same number of cables.
2) The power per corridor is equally distributed among multiple cables of equal size.
3) Each cable is connected to each main and auxiliary engine, thus ensuring that any load can be powered from any source.
4) Each PEBB outputs a single voltage. Different loads operate with different input voltages, but these are selected from a small set of possible voltages, and loads of like voltage are grouped as necessary to fill PEBBs.
5) The main bus operates at a single voltage; thus, all PEBBs operate at a single input voltage. In our example, this is 12KVdc, or ± 6 KVdc.
6) All PEBBs are a single, standard size. We selected a capacity of 166.67kW per PEBB.
7) Each PEBB stack has the same number of PEBBs. We selected stacks of six PEBBs, yielding 1MW per stack.
8) Stacks are not subdivided; that is, we only install full capacity stacks. If more PEBBs are installed than are required, the extra PEBBs can act as installed spares. Thus, the number of PEBB stacks is only increased by integer quantities.
9) The ship is segmented into watertight bulkhead divisions, which is the area between two sequential watertight bulkheads. We refer to these as sections or compartments.
10) All power inputs and outputs occur within each section individually. That is, every load physically located in a watertight division is fully supplied from the corridors within that division. Similarly, all power from a generator is put onto the bus within the section that the generator is physically located in. Power is transferred through watertight bulkheads only on the main bus.
11) For calculation purposes, all loads within any section are aggregated into a single equivalent load for each voltage type, without regard of where it is actually connected within the section.
12) Number of corridors must be an even number, in this case 4 corridors.
13) $N-1$ corridors must supply the total load.
14) All corridors within a section have as close to the same number of cable connections as possible, with

a maximum difference of one connection.

15) The total number of load cable connections is equal to or greater than the total electrical load within a section divided by the total power per PEBB stack; thus, there must be at least one connection per PEBB stack.
16) Generation power is equal or greater than the total load power.
17) The power flow in any cable in any section must never exceed the cable capacity, given the $(N-1)$ working corridors constraint.

## III. The Problem Solution Process

During the problem analysis the following steps are taken:

1) Obtain the *Load Demand* for all ship sections.
2) Lay out a one-corridor distribution system to obtain the minimum corridor section.
3) Decompose obtained load demand according their voltages.
4) Obtain minimum number of PEBB Stacks per Compartment, given that $(N-1)$ corridors must supply the total demand.
5) Initially, the PEBB Stacks are configured so that all 6 PEBBs in a stack obtain power from a single connection and cable, assuming that one cable is of sufficient capacity to supply the power required by a full PEBB stack. This connectivity is changed using a PEBB stack connectivity factor, here shortened to *Multiplier*, which is defined as the allowed number of cables connected to each stack of PEBBs. In this case, the set of Multipliers is (1 2 3 6). Each of these Multipliers defines a *Design*. For each design, we define the number of PEBB Stacks per compartment $StackConnections_{Design_X} = BaseConnectivity \cdot Multiplier$.
6) Distribute connections in a compartment over all corridors, maximizing diversification. A *First Fit Decreasing* algorithm is used. The most power-dense compartments get allocated first.
7) Distribute, sequentially, connections over cables within corridors. A First Fit Decreasing algorithm is also used here. The most power-dense compartments get allocated fist.
8) A *Balancing Algorithm* is implemented to improve load distribution among cables.
9) Once the Load Distribution and a predefined Generation Distribution are defined, the maximum expected flow in each corridor can be obtained with the Push-Pull Algorithm, [6].
10) In the last step of the analysis, the results obtained for all Designs are compared and trade-offs are obtained to determine the desired connectivity. The ultimate parameter that characterizes each Design is the Multiplier, which determines the allowed connectivity. Other parameters are left unvaried (such as the number of iterations in the balancing loop).

A depiction of this process is presented in Fig. 2. In the following sections a more detailed explanation of the steps is given.

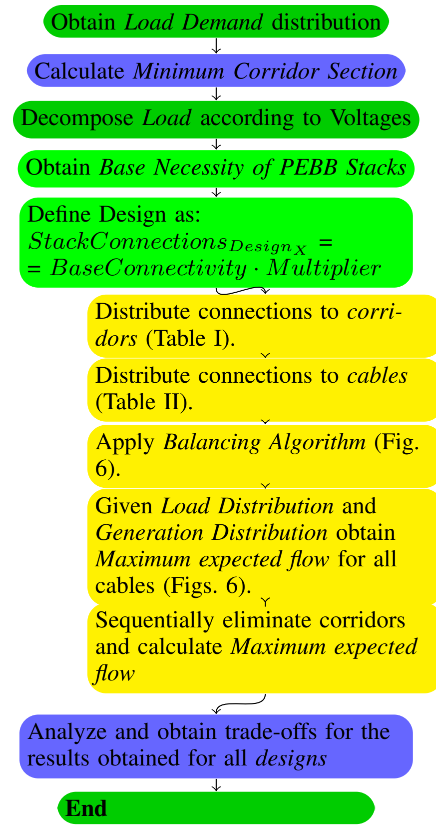


Fig. 2. Flow chart for the design process of the Power Corridor

### A. Particularities of the network topology

Loads and generation are distributed up to a certain granularity throughout the ship. The topology of the system is designed so that the power cables can receive energy input at multiple separated points; this way the system can be simplified as a bus bar or single cable system, as represented in Fig. 3. The maximum power flow at any section will be less than the total aggregated load demand and will depend on the arrangement chosen of generation and load distribution, for each cable in the power corridor. The algorithm used to calculate the *Maximum Expected Power Flow* is presented in the following section.

### B. Algorithm to Calculate the Maximum Expected Power Flow

Throughout the design exploration, indicators must be defined to be able to evaluate and compare the designs. The first and foremost important condition is that every design has to meet is its capability to transport power without overloading the lines, for any generation arrangement within the system. To do this, a *Push-Pull algorithm* is used to evaluate worst possible scenarios within each cable. To achieve this, the maximum possible power flow through a certain cable section is calculated using the following expression:

$$MaxFlow = max \begin{pmatrix} min(\sum L_R, \sum G_L) \\ min(\sum L_L, \sum G_R) \end{pmatrix} \quad (1)$$

Equation (1) is a comparison of the power that can be pushed through a section in a cable, given the total amount

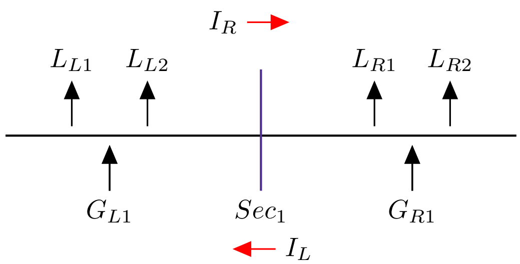


Fig. 3. Diagram Explaining the Push-Pull Algorithm

of energy generated on one side and how much power can be pulled given the loads on the opposite side. The Maximum Flow can be obtained through the comparison of the two possible combinations. An illustration to better visualize this logic is given in Fig. 3.

### C. Description of the Balancing Algorithm

A second algorithm is designed to allocate the loads to the cables more uniformly and efficiently. The mission of this algorithm is to go through the most heavily loaded lines within a corridor, and check if there is equipment that is also connected to other underloaded lines through any other connections that it may be using, then shift some of the load to a more lightly loaded line. Thus, the excess energy is distributed among the available least loaded lines in an iterative process.

An important thing that should be pointed out is that this is only possible to do if *connectivity* exists between the loads and the cables to create alternative *paths*. For this reason, with Multipliers, described in section V, the number of connections available to each stacks is increased when doing design exploration.

A pseudo code describing the underlying processes of the *Balancing Algorithm* is given in Fig. 4. The end result of this code is an even distribution of the power demand among all cables, or at least the best possible configuration given the allowed connectivity. Fig. 5 shows the Maximum Expected Power Flow before executing the Balancing Algorithm and Fig. 6 shows the same results after applying the algorithm. Note that red areas in Fig. 5, denoting overloaded segments of cables are no longer in Fig. 6.

## IV. Design Exploration Algorithm

As mentioned before, the approach chosen is iterative. This raises the need to lay out a large number of tentative distribution networks and to evaluate them in a fast and efficient way. The solution to this problem is provided by a program that creates and analyzes tentative connection distributions to the corridors.

In this iterative process, the maximum expected flow through a cable section depends on the aggregated load and generation on both sides of the cable section.

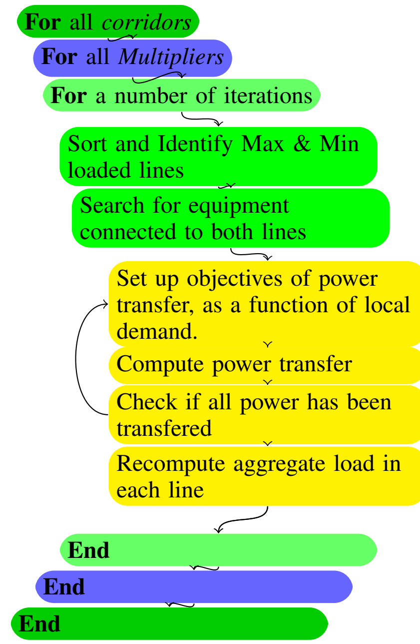


Fig. 4. Pseudo code for *Balancing Algorithm*

### A. Parametric and Algorithmic Definition of the Power Corridor

In the program, the *Power Corridor* is defined in a parametric way, so that each design can be represented by a set of parameters. The complete definition of the notional power corridor, within the routine, is given by the following set of parameters:

1) Corridor number: there are a total of 4 corridors, two each in decks 2 and 4 respectively.
2) Corridor compartment number: each corridor is divided into *load sections*, each corresponding to a load center. This *load sections*, for the example presented, create a total of 12 compartments, each with its own power requirements.
3) Number of PEBB Stacks: within a compartment, depending on its power requirement, a minimum number of PEBB stacks will be necessary. The power requirement of a compartment is defined by a load demand in *MW* and the voltages at which it must be serviced at. In this design the voltages can be: 12kV DC, 1000V DC or 450V AC.
4) Number of cables available to each stack: every stack will be able to connect up to 6 different cables, the base design is done with one connection per PEBB stack. This connectivity is increased with Multipliers. For example, if we have 6 PEBBs per stack, we consider as alternative designs: 1 connection per 6 PEBBs, 2 per 6 PEBBs, 3 per 6 PEBBs and 6 per 6 PEBBs. So in order to obtain *PEBB Box Groups* of the same number of PEBBs, the Multipliers are factors of the number of PEBBs per stack. In this case the vector of Multipliers is [1 2 3 6].

Given these parameters, an arrangement must be created such that every piece of equipment gets its demanded power in the format specified (12kV DC, 1000V DC and 450V AC), without overloading any section of the distribution network.

Each PEBB stack is able to connect to a specific number of cables at a time, defined in the vector of Multipliers. The problem at hand is reduced to a *bin packing problem* or *N-partitioning problem*. This problem can be defined as packing objects of different volumes (power demanded from each group of PEBBs) into a finite number of bins or containers each of volume *V* (cable capacity) in a way that minimizes the number of bins used [7]. In our case, we have to pack load demands for each PEBB Box Group, in the PEBB stack, into the cables while minimizing the total number of PEBB Box Groups required to distribute the load. Given enough connectivity this will be achievable in the allowed number of connections.

In terms of computational complexity theory, this problem is *NP-hard*. Many heuristic algorithms have been developed in order to provide feasible solutions to this type of problem, although not completely optimized.

A hybrid, 2-stage, algorithm is used at this stage. In the first stage, a first fit decreasing algorithm is used. It operates by first sorting the items to be inserted in decreasing order considering their sizes. Particularly, in this case the load compartments, depending on how power dense they are.

Given an *Optimal value of bins* **OPT**, it can be proved that this algorithm uses no more than $\frac{11}{9}\mathbf{OPT}+1$ bins. This degree of precision is considered to be adequate for this stage of the design. Moreover, since the main objective of the tool is to be an efficient design explorer and arranger, a more complicated tool could increase exponentially the run times in this *NP-hard* problem.

## V. Application to the Notional Ship

In order to obtain an optimized distribution for a series of tentative designs, the first fit decreasing algorithm is programmed to do design exploration. Each design is constructed from the definition of a set of required number of PEBB boxes in each given compartment. This installed capacity must be able to supply any loading condition. Connectivity is increased with Multipliers that can be chosen by the designer in order to be able to choose the best possible configuration. The Multipliers available are defined, as mentioned before, as factors of the number of PEBBs in each stack. This allows one to define how the PEBBs can be evenly grouped.

The definition of the minimum number of PEBB boxes is done through the classification of the equipment working during the most demanding condition, Battle Condition. This way the number of stacks needed is determined by the load demanded and the different conditions in which electricity must be supplied (12kV DC, 1000V DC and 450V AC).

Because of the particularities of the application in hand, some additional features must be considered during the design problem. The conditions to satisfy are the following:

1) The failure of an entire corridor must not affect the operation of the ship in any way. For this reason the dimensioning is done starting from 3 corridors. This way the loads that need to be connected to 3 corridors will be connected to a minimum of 4. In conclusion, the loss of any set of connections to any corridor must not alter the operation of any piece of equipment.
2) Enough redundancy must be given so that a feasible arrangement can be created if a certain cable fails. The designs allow between 1 and 6 connections to different cables per PEBB stack and, given the ability to work under the loss of an entire corridor, this will give more than enough margin.

To have a preliminary dimensioning of the corridors, a single corridor layout is first studied, taking as reference a notional ship already used in previous papers [5]. This is done to identify the bottle necks of the multiple input/output system and calculate its overall capacity. What one should look for is concentrated loads or generation capacity. In the case of this design, the bottle neck is provided by the biggest engine room, since it has to output 58 $MW$ of power within the space of one compartment.

One option, to reduce this concentrated energy input, would be to output in different compartments. However, this would mean directly transferring this power to the propulsion engines which, by itself, would reduce the redundancy given by the different paths of the four power corridors. Another option would be to penetrate bulkheads to input power in other sections than where the power is generated. At the time of this writing, this would be counter productive. 58 $MW$ is taken as the base capacity of the corridors. It should be noticed that a total of 94 $MW$ can be driven through this 58 $MW$ system, thanks to multiple inputs and outputs at the different sections. As described, the total capacity of each corridor is provided by dividing $58/3 \simeq 20MW$. Given this requirements, using data from past designs, 14 cables [8] of 1.5 MW + 2 reserves are used, giving the distribution system $84MW$ of capacity.

An approximately even load distribution along the cables is obtained first using the first fit decreasing algorithm to efficiently allocate the load from a compartment in a per corridor basis. The results of the latter are shown in Table I. Secondly, the set of cables made available to each PEBB box stack is done sequentially using also the first fit decreasing algorithm. This way, diversification of the connections is maximized from the load in each compartment to each corridor while balancing the power demanded from every corridor.

With this in mind, the algorithmic definition described is programmed in order to attempt a even distribution of the power demanded, from each corridor and for all the Multipliers defined in the design exploration. This algorithm makes it easy to explore multiple configurations in a fast and cheap manner. An example output of this algorithm is given in Table I.

Once Table I is defined for all the Multipliers, the connection tables (an example for a corridor is given in Table II) can be defined in a sequential way using the results from the first fit decreasing algorithm. The connections to each power source are given from a predefined layout, where all the main generators have the possibility to connect to any cable within any of the 4 corridors. It is assumed that the power demanded in each the compartments can be considered to be uniformly distributed along the existing connections, in a first approximation. By doing this it is possible to calculate the Table IV (also for a corridor). These tables indicate the power

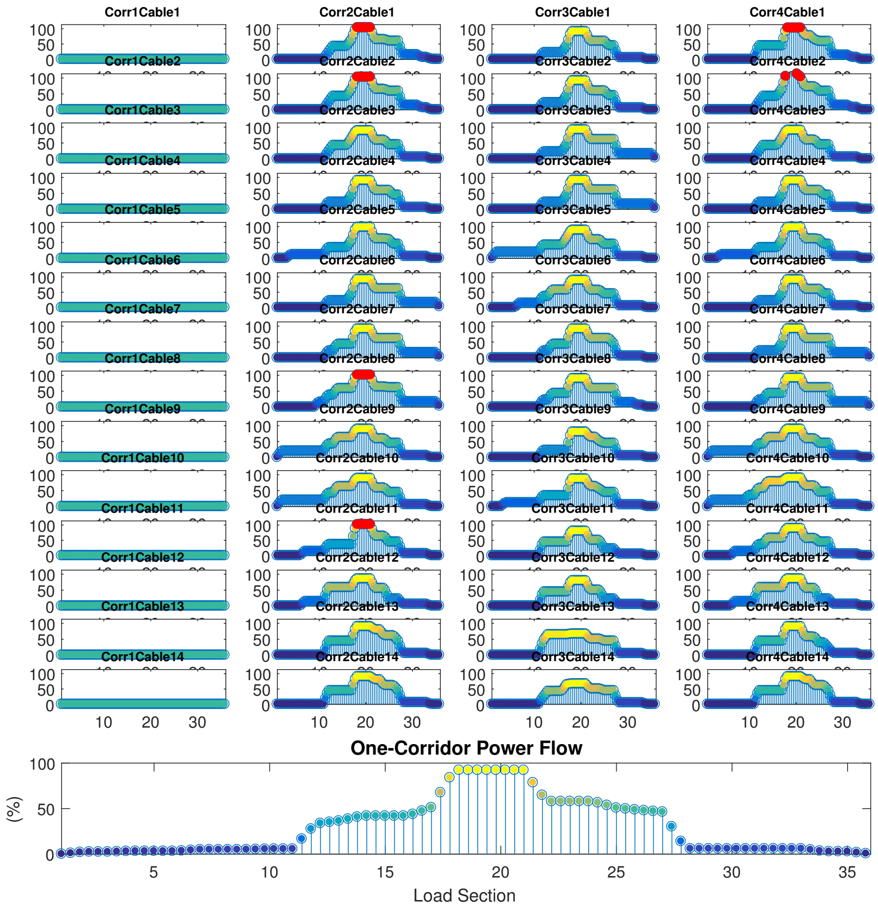


Fig. 5. Maximum Power flow along all cables in all corridors before performing load balancing algorithm. This representation helps compare the different designs, overloaded sections of the cable are plotted in red, like in the upper right corner of the figure.

TABLE I. EXAMPLE OF AN INITIAL EFFICIENT DISTRIBUTION FROM COMPARTMENTS TO CORRIDORS.

| Comp. | P[MW] | Min. Conn. | Tot. Conn. | Corridors 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|
| 9 | 28.4 | 32 | 48 | 12 | 12 | 12 | 12 |
| 7 | 26.5 | 29 | 44 | 11 | 11 | 11 | 11 |
| 4 | 17.72 | 21 | 32 | 8 | 8 | 8 | 8 |
| 5 | 5.53 | 7 | 11 | 2 | 3 | 3 | 3 |
| 6 | 5.83 | 7 | 11 | 3 | 3 | 2 | 3 |
| 8 | 3.43 | 4 | 6 | 1 | 2 | 1 | 2 |
| 12 | 1.76 | 2 | 3 | 0 | 1 | 1 | 1 |
| 1 | 1.48 | 2 | 3 | 1 | 1 | 0 | 1 |
| 2 | 0.53 | 1 | 2 | 0 | 1 | 0 | 1 |
| 3 | 1.05 | 1 | 2 | 0 | 1 | 0 | 1 |
| 10 | 1.05 | 1 | 2 | 0 | 1 | 0 | 1 |
| 11 | 1 | 1 | 2 | 0 | 1 | 0 | 1 |
| Total | 94.04 | 108 | 166 | 38 | 45 | 38 | 45 |

demanded in a compartment from any cable connection to the corridors. Note that these tables are merely intermediate result examples, and do not correspond to the final configuration presented in Fig. 6.

At this point the power output and power input in the circuit are completely defined. Now, by using the algorithm described in subsection III-B, the *Maximum Power Flow* can be determined for every cable segment going through a specific compartment. The results of this process are illustrated in Fig. 6, where these values are divided by the bus voltage to obtain the magnitude of the current. The maximum allowable current in this given design is 125A, due to the characteristics of the chosen base cable.

The aggregated load in each cable is calculated by adding all the loads in the particular cable. This is done by adding the columns of table in Table IV, for every corridor and design. The Multipliers increase with the design number and can be chosen by the designer, in this case values $[1, 2, 3, 6]$ are used.

The Balancing Algorithm is implemented so that, once the initial distribution is obtained from the first fit decreasing algorithm, loads connected to the most loaded lines can search for space in the least loaded lines, in an iterative manner. They can switch completely or partially if the load uses multiple connections to extract power from the distribution network. This algorithm stops working once a maximization of the diversification of the loads along the lines is obtained. The

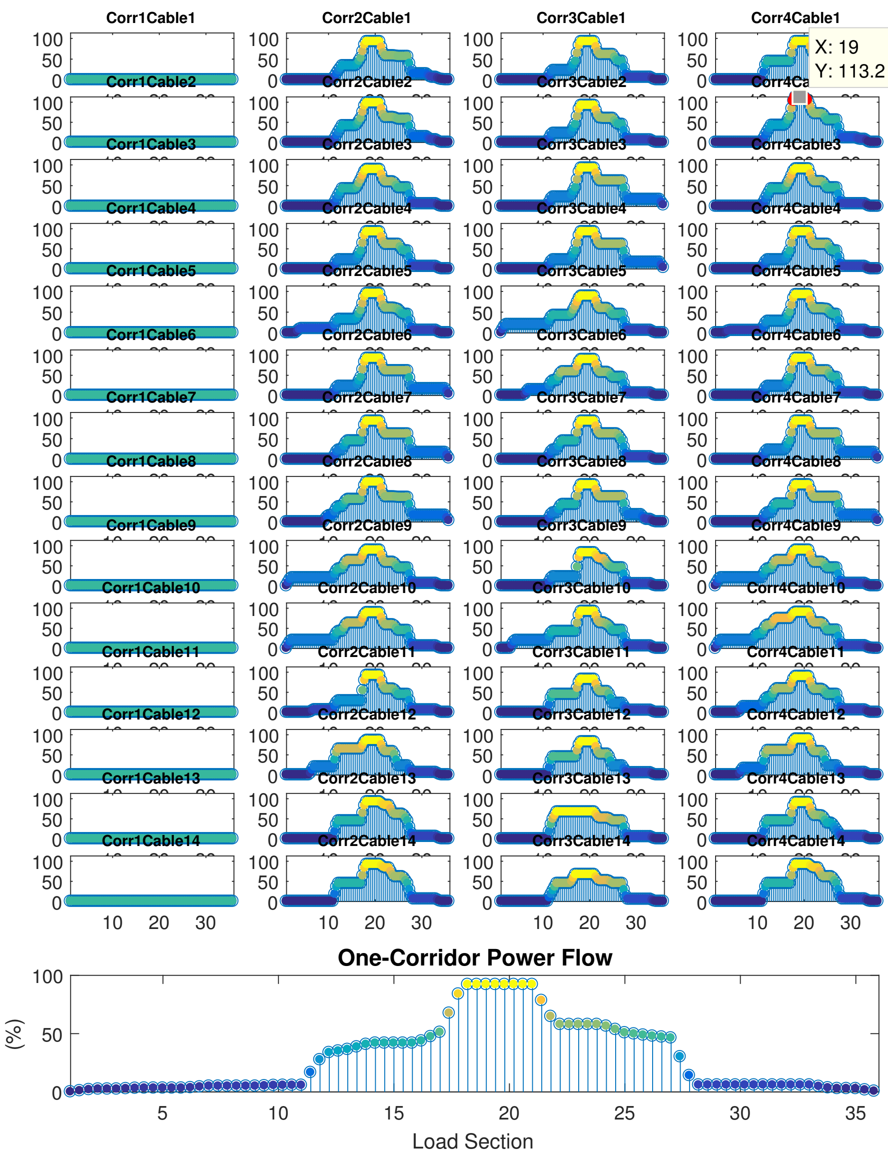


Fig. 6. Maximum Power flow along all cables in all corridors after performing load balancing algorithm. This representation helps compare the different designs, overloaded sections of the cable are plotted in red. Comparing the upper right corner to Fig. 5, we can see that the Balancing Algorithm has successfully shifted the power from the overloaded to the underloaded lines.

TABLE II. CONNECTION FROM EACH AGGREGATED LOAD TO EACH CABLE IN A CORRIDOR.

| | Cable number in Corridor $X$ | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Comp. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 |
| 5 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 |
| 6 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| 9 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
| 10 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |

TABLE III. CONNECTION FROM EACH GENERATOR TO EACH CABLE IN A CORRIDOR.

| | Cable number in Corridor *X* | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Comp. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

TABLE IV. POWER DEMANDED [MW] IN EACH SHIP SECTION AND CABLE, FOR A CORRIDOR.

| | Cable number in Corridor *X* | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Comp. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1887 | 0.1881 | 0 | 0 |
| 2 | 0.1326 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0.2621 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0.1903 | 0.0485 | 0.0628 | 0.0484 | 0.2707 | 0.2708 | 0.2710 | 0.2707 | 0.2646 | 0.2647 | 0 | 0 | 0.6047 | 0.5959 | 0.6264 | 0.6258 |
| 5 | 0.1562 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1949 | 0.1877 | 0.2003 | 0.2098 | 0.1982 | 0.1987 |
| 6 | 0 | 0.2084 | 0.2084 | 0.2084 | 0.2084 | 0.2084 | 0.2084 | 0.2084 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0.5264 | 0.4867 | 0.4854 | 0.4867 | 0.5264 | 0.5264 | 0.5264 | 0.5264 | 0.5264 | 0.5264 | 0.5966 | 0.6033 | 0 | 0 | 0.5264 | 0.5264 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2145 | 0.2145 | 0.2145 | 0.2145 | 0 | 0 | 0 | 0 |
| 9 | 0.5651 | 0.5651 | 0.5651 | 0.5651 | 0.5651 | 0.5651 | 0.5651 | 0.5651 | 0.5651 | 0.5651 | 0.5651 | 0.5651 | 0.5651 | 0.5651 | 0 | 0 |
| 10 | 0 | 0 | 0.2500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11 | 0 | 0 | 0 | 0.2621 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2197 | 0.2197 |

TABLE V. POWER INPUT [MW] IN EACH SHIP SECTION, FOR A CORRIDOR.

| | Cable number in Corridor *X* | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Comp. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 1.3810 | 1.4235 | 1.4072 | 1.4072 | 1.3900 | 1.4512 | 1.3965 | 1.3965 | 1.4966 | 1.4065 | 1.3831 | 1.4245 | 1.2395 | 1.2313 | 1.4245 | 1.4512 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0.7786 | 0.8026 | 0.7933 | 0.7933 | 0.7837 | 0.8182 | 0.7873 | 0.7873 | 0.8438 | 0.7930 | 0.7798 | 0.8031 | 0.6988 | 0.6942 | 0.8182 | 0.8438 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0.0881 | 0.0908 | 0.0898 | 0.0898 | 0.0887 | 0.0926 | 0.0891 | 0.0891 | 0.0955 | 0.0897 | 0.0882 | 0.0909 | 0.0791 | 0.0785 | 0.0891 | 0.0955 |
| 11 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

TABLE VI. MAX. POWER FLOW [MW] IN EACH SHIP SECTION, FOR A CORRIDOR.

| | Cable number in Corridor *X* | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Comp. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1859 | 0.1859 | 0 | 0 |
| 2 | 0.1326 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1859 | 0.1859 | 0 | 0 |
| 3 | 0.1326 | 0.2621 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1859 | 0.1859 | 0 | 0 |
| 4 | 0.4491 | 0.5785 | 0.3165 | 0.3165 | 0.3165 | 0.3165 | 0.3165 | 0.3165 | 0.3165 | 0.3165 | 0 | 0 | 0.5024 | 0.5024 | 0.3165 | 0.3165 |
| 5 | 0.6465 | 0.5785 | 0.3165 | 0.3165 | 0.3165 | 0.3165 | 0.3165 | 0.3165 | 0.3165 | 0.3165 | 0.1974 | 0.1974 | 0.6998 | 0.6998 | 0.5139 | 0.5139 |
| 6 | 1.0915 | 1.2999 | 1.5000 | 1.5000 | 1.2999 | 1.2999 | 1.2999 | 1.2999 | 1.3060 | 1.3060 | 1.3060 | 1.3060 | 0.6998 | 0.6998 | 0.7461 | 0.7461 |
| 7 | 1.1729 | 1.3133 | 1.3415 | 1.3536 | 1.0915 | 1.0915 | 1.0915 | 1.0915 | 1.3060 | 1.3060 | 1.3060 | 1.3060 | 0.6998 | 0.6998 | 1.0403 | 1.0403 |
| 8 | 1.1729 | 1.3133 | 1.0512 | 1.0512 | 1.0512 | 1.0512 | 1.0512 | 1.0512 | 1.0573 | 1.0573 | 0.9383 | 0.9383 | 0.6998 | 0.6998 | 1.0403 | 1.0403 |
| 9 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.2649 | 1.2649 | 1.0403 | 1.0403 |
| 10 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.2649 | 1.2649 | 1.0403 | 1.0403 |
| 11 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.5000 | 1.2649 | 1.2649 | 1.0403 | 1.0403 |
| 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2197 | 0.2197 |

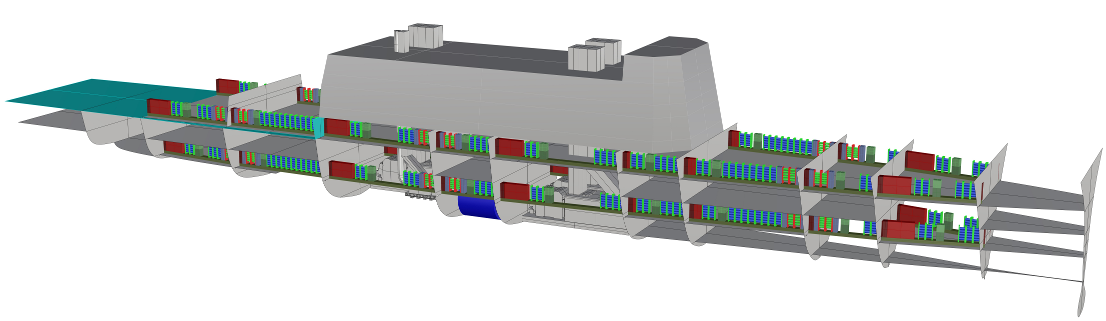

Fig. 7. General view of the Power Corridor in the notional ship.

TABLE VII. DESCRIPTION OF INPUT DISTRIBUTION IN DESIGN EXPLORATION PROGRAM.

| Variable | Description |
|---|---|
| $P_L$ | Vector with load in each compartment. |
| $P_G$ | Vector with generation in each compartment. |
| $P_C$ | Power Capacity of each cable. |
| StacksPerCompartment | Vector with min stacks in each compartment. |
| RedVect | Vector with Multipliers for design exploration. |
| NumberOfCables | Total number of cables in all corridors. |
| NumCorridors | Total number of corridors. |
| VoltBus | Voltage in Bus for current calculation. |
| ObjPowInCable | Is the capacity of the cable, can be varied for optimization. |

TABLE VIII. DESCRIPTION OF OUTPUT DISTRIBUTION IN DESIGN EXPLORATION PROGRAM.

| Variable | Description |
|---|---|
| ConnContMatrix | Matrix relating number of connections from compartments to corridors, an example of this output is provided in Table I. |
| PowPerConnInComp | Gives the average power per connection in each compartment. |
| PowConnAlongLine | Indicates the number of power tap offs from each cable within each corridor. |
| ConnTables | An array of ones and zeros expressing the existence of a connection between the load in a compartment to a cable. Given a corridor, Table II can be example of the output. |
| PowConnTables | An array of ones and zeros expressing the existence of a connection between the generation in a compartment to a cable. Given a corridor, Table III can be an example of the output. |
| PowerPerConnTables | An array expressing the power demanded from a connection, from a compartment to a cable. Given a corridor, Table IV can be example of the output. |
| PowerPerPowConnTables | An array expressing the power inputed in a connection, from a compartment and to a cable. Given a corridor, Fig. V can be example of the output. |
| MaxPowerFlowPerCorrAndComp | An array expressing the *Maximun Powerflow* in a section along a compartment. Given a corridor, Table VI can be example of the output. |

last conditions to check out are: that the amount of power generated is equal to the total amount of power consumed and that the Push/Pull Algorithm does not detect overloaded lines. The effect of the Balancing Algorithm can be seen by comparing Fig. 5 to Fig. 6. In these tables we find 4 columns and 14 rows of plots; each column corresponds to a corridor and each row corresponds to a cable within the corridor. In each plot the Maximum Current, obtained from Maximum Power Flow, is is represented for a longitudinal position on every cable.

### A. Inputs and Outputs

The data input and output in the program is accomplished through arrays of rational numbers.

The information needed by the program is described in detail in Table VII and, in the same way, the output array variables are described in Table VIII.

## VI. RESULTS

Examples of the intermediate results are presented in Tabs. II, IV and VI, all of which are expressed in the same format. They are saved as multidimensional arrays. The size of these arrays is: [ *number of compartments*, *number of cables*, *number of corridors*, *number of Multipliers* ]. This way one array contains the information for all the designs that are being explored and there will be one of these arrays for every variable monitored.

The main results of the paper are presented in Figs. 5 and 6, where the result of a power corridor failure is presented. To check that the load is balanced, through this same framework, we eliminate any full corridor, and then analyze if any line is overloaded. The conclusions that can be drawn from the analysis performed are two. *First*, an efficient load distribution is easily obtained with 3 connections per PEBB stack. This way the necessary connectivity is reached. Furthermore, one must bear in mind that one must be able to loose an entire corridor and still have the necessary capacity in all compartments. This can easily be checked in Table I, where in no scenario any compartment ends up with fewer available connections than the minimum specified. *Second*, the main bottle neck as commented in section V is the high power input in one of the generation rooms, specifically 58 MW. The ability to reduce this power concentration would reduce the necessary capacity and size of the corridor.

## VII. CONCLUSIONS

In this paper we have detailed algorithms and process necessary to model the electrical distribution system of an all-electric warship, using the PEBB-based integrated power and energy corridor.

Using these algorithms, we are able to design a balanced network of connections to deliver full power between the generators of the loads using N-1 corridors. We demonstrated the process on a notional warship.

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