ANALYSIS OF VARIOUS ALL-ELECTRIC-SHIP ELECTRICAL DISTRIBUTION SYSTEM TOPOLOGIES

J. Chalfant and C. Chryssostomidis

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Analysis of Various All-Electric-Ship Electrical Distribution System Topologies

J. S. Chalfant and C. Chryssostomidis
Design Laboratory, MIT Sea Grant College Program
Massachusetts Institute of Technology (MIT)
Cambridge, MA, USA
Email: {chalfant, chrys}@mit.edu

***Abstract*—As advances in technology mature, the need is evident for a coherent simulation of the total electric-drive ship to model the effect of new systems on the overall performance of the vessel. Our laboratory has been developing an integrated architectural model in a physics-based environment which analyzes ship variants using a standard set of metrics, including weight, volume, fuel usage and survivability. This paper discusses advances in the model including the use of operational scenarios, incorporation of a survivability metric, and streamlining the performance of model. The model is employed herein to compare two possible distribution system topologies: a ring bus and a breaker-and-a-half. The ring bus is heavier and larger but more survivable. Fuel usage is equivalent in the two variants.**

I. Introduction

The U.S. Navy warship of the future is envisioned to have extremely power-intensive weapon and sensing capabilities including such concepts as pulse weapons, dual-band radar, and integrated communications. One proposed method of achieving such power requirements is the Integrated Power System (IPS), which, through making use of electric-drive propulsion, provides the flexibility to use shipboard power for a mix of service and propulsion loads. This allows a ship to operate with less total installed power by trading off maximum speed for maximum weapon and sensor load. The Electric Ship Research and Development Consortium (ESRDC) is a consortium of eight research universities supported by the Office of Naval Research (ONR) to collaborate on research in this area. ESRDC is performing investigations into the dynamic performance of various possible electrical distribution systems with the goal of achieving greater quality of service and higher power density; the three main systems under study are Medium-Voltage AC (MVAC), High-Frequency AC (HFAC) and Medium-Voltage DC (MVDC). The studies are performed on two levels: high-resolution models that investigate the dynamic performance of the systems and look to solve inherent issues like grounding, fault detection and isolation, and bus stability; and lower-resolution models that investigate overall performance of various topologies.

Our laboratory is involved in a body of work to develop an overall architectural model of an all-electric ship using a physics-based environment to perform fully-integrated simulation of electrical, hydrodynamic, thermal, and structural components of the ship operating in a seaway. The goal of this architectural model is to develop an early-stage design tool capable of performing tradeoff studies under a standardized set of metrics. In the past we have used this model to compare a medium-voltage DC electrical distribution system to a hybrid DC/AC electrical distribution system, analyzing the effects on weight, volume and efficiency under a maximum loading condition [1]. We also used the model to investigate the effects of new propeller and motor designs such as a high-speed propeller or a contra-rotating propeller/motor combination [2].

Continued expansion of this model allows us to address a wider range of problems. We now run the model through a typical operational scenario, thus comparing topologies through a range of electrical loading schemata. In addition, we have added a survivability analysis metric.

In this paper, we apply the model to compare a ring bus topology to a breaker-and-a-half system. Each variation is analyzed with respect to weight, volume, efficiency and survivability.

The paper is organized as follows. Section 2 describes the overall architectural model and details some of the programming components and new features. Section 3 provides a description of the notional ship used in modeling and the equipment used within this ship. Section 4 presents the results of the tradeoff studies. Conclusions and recommendations for future work are addressed in Section 5.

II. Architectural Model

The code is modularized. Depending upon the scenarios to be analyzed in the tradeoff studies, different modules can be incorporated as desired. Resistance, propulsion power and fuel usage modules are described in [2]. In [1], we added an electrical distribution system. Here, we have modified the code to be object-oriented, improved the operational scenario analysis of [2] to cover the electrical distribution system as well as propulsion, added a survivability analysis module based on [3], and added the capability to analyze a multiple-blast survivability scenario.

Much of the architectural model is written in MATLAB [4] using object-oriented programming features. A *ship object* class standardizes the information recorded for each piece of

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equipment. This class structure allows the determination of such key information as weight, volume and losses based on factors such location, size and loading. Child classes address specific instances of ship objects including power generation modules (PGMs), propulsion motor modules (PMMs), power conversion modules (PCMs), power distribution modules (PDMs), loads and buses. Details of these components as envisioned by the Naval Sea Systems Command (NAVSEA) in the implementation of electric warships can be found in the Next Generation Integrated Power System (NGIPS) Roadmap produced by NAVSEA [5].

As part of the architectural model, we created an equipment library with documented examples of many specific pieces of equipment. As an example, the PGM library includes the Rolls-Royce MT30 and RR4500 and the General Electric LM2500 and LM500. The BUS library includes standard marine cabling for both DC and AC applications, with single and multiple connector options, at various voltages and ampacities.

The object-oriented nature of the program combined with the presence of the equipment library makes setting up various electrical distribution systems fairly straightforward. Usage could be eased even further through the implementation of a GUI to automatically record the node connections for flow analysis.

One problem with the object-oriented features in MATLAB is that they run slowly. Performance was greatly improved by using the object-oriented portion as a wrapper to be used in setting up systems, then extracting key data to use in calculations. This extraction process is transparent to the user. Run time for a simple ring bus example was thus improved from 15 seconds to 3 seconds.

A. *Electrical Distribution Analysis*

Electrical flow is assessed using a max-flow, min-cost algorithm. Dijkstra's algorithm [6] calculates the lowest weight path from a source to a destination in a directed, weighted graph and returns the weight (cost) of the path and the sequence of nodes in the lowest cost path.

We set the system up in reverse so flow proceeds from the loads to the generators; losses in equipment traversed are added to the flow along the path. A super-sink is connected to all the generators with a path weight corresponding to specific fuel consumption, so the loads are satisfied by the lowest-cost path/generator available. Loads are filled in priority order, and network capacity is subtracted along the path as each load is satisfied, thus achieving a maximum (weighted) flow at minimum cost.

B. *Operational Scenario*

We apply a variety of loading scenarios dependent upon different operational conditions. The basic assumption is that in different types of operations, different loading conditions will exist; for example, a ship is more likely to have the radar and weapons operating at maximum power in battle than when cruising in peacetime, and is less likely to be operating the laundry. An operational profile is composed of the percent of time per year that a ship operates at each loading condition and speed. When combined with a usage profile of the gas turbine generators, this produces a percent loading of the generators which in turn gives a fuel usage for that condition/speed combination. The speed/condition profile that we employ [2] is based upon actual data for U.S. Navy destroyer operations in the 1990's [7] along with a condition profile from NAVSEA [8]. Table I lists the power required by an example set of loads at cruise and battle conditions.

C. *Survivability*

We invoke a twofold survivability metric to measure two distinct issues. The first metric calculates the maximum value of all loads that can be serviced, proceeding in priority order, thus indicating an overall ability to provide and distribute power in the face of damage. The second metric determines the highest priority load that cannot be filled while satisfying all higher priority loads; this provides an indication of the severity of the impact of lost loads.

Calculation of the metric is described in [3] and summarized here. For a given a set of loads, we establish a weighted, prioritized list for servicing the loads. Then we impose damage upon the ship. Blasts consist of a center of impact and a radius of destruction; all equipment that intersects the sphere is assumed destroyed. Blast centers are located using a Monte Carlo method, randomly placing blast locations throughout the length, breadth and depth of the ship from keel to top of mast. Blast radii are selected to be one-half, one and two times the average bulkhead separation.

Following each blast, damaged equipment is removed from the directed graph and the prioritized electrical analysis is conducted to determine which loads are filled. The overall survivability score is the sum of the weighting of the load times the amount of power (or other resource such as cooling capacity) provided to that load. The survivability tier score is the highest priority load that is not completely filled. This analysis process identifies loads that cannot be filled due to either a lack of generating capacity or a lack of connectivity, or that are damaged themselves. The scores are then averaged over a large number of blasts. The survivability metric can be calculated for single or multiple blasts.

III. Notional Ship

The ESRDC is currently using a baseline topology to compare modeling efforts [9]; see Figure 2. This topology is supported by a list of 22 lumped-parameter loads in four zones, plus selected propulsion motors, radar, pulse weapon, and generators. Specifics of the lumped loads are shown in Table I. The propulsion motors are two Converteam Advanced Induction Motors (AIM) which use a maximum of 35MW each; the power required for our notional ship with this power train to achieve several discrete speeds is shown in Table II. The load shown is the total load required to move the ship at the indicated speed; load per motor is half the load value shown. The radar is assumed to require a maximum of

3.75MW and the pulse weapon is assumed to require 10MW at maximum firing rate.

The ship is powered by two Rolls-Royce MT30 and two General Electric LM500 gas turbine engines with associated generators, capable of producing 36MW and 5MW of power each.

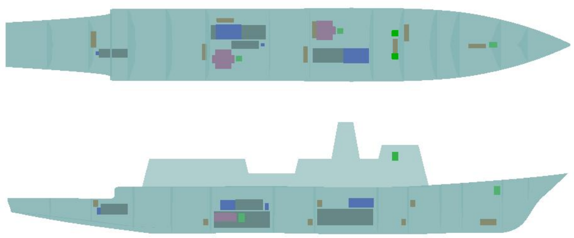

Fig. 1. Notional Ship Layout, generated in Paramarine [10].

We have designed a notional ship in Paramarine [10] which locates this baseline topology and its supporting equipment in space; see Figure 1. We used a hullform based on DDG-51 but modified to accommodate the larger engines and an integrated mast. Machinery is located as follows:

- The generators are grey in the figure. One MT30 is located in each main machinery room; one LM500 is located in the aft main machinery room, inboard and above the MT30; and the second LM500 is located aft, in an auxiliary machinery room.
- The rectifiers are located adjacent to their associated generator; they are blue in the figure.
- The propulsion motors are placed in separate zones. The port motor is in the forward main machinery room, and the starboard motor is in the aft main machinery room. They are pink in the figure, with green motor drives located directly forward of them.
- The ship is divided into four zones. There is a PCM-1A, colored brown in the figure, located forward and aft in each zone. In general, the forward one is starboard and low, while the aft one is port and high, but the starboard one is often constrained toward the centerline due to the hull shape. This layout is for the ring bus topology; the breaker-and-a-half topology has only one PCM-1A in each zone, closer to the center of the zone. A PCM-1A is the power electronics equipment that converts power at bus voltage to the power types used within the zone, including various voltages and frequencies of AC and DC power.
- The DC/DC converter for the pulse weapon can be seen in the bow, just below main deck. The DC/DC converters for the radar are port and starboard in the superstructure. They are green in the figure.

We chose to locate the main radar amidships on the superstructure, so we modified the baseline ESRDC topology to tie the radar into zones 2 and 3 on the port and starboard sides instead of aft of zone 4, and moved the energy storage module to maintain proximity to the radar. This is the only portion of the topology that was changed; our modified topology is shown in Figure 3.

TABLE II
NOTIONAL SHIP TOTAL MOTOR LOADS.

Speed (kt)	Load (kW)
0	0
5	203
10	1,415
15	4,696
20	10,996
25	24,085
30	60,407

IV. Tradeoff Study

We employed our architectural model to compare a ring bus to a breaker-and-a-half system while maintaining the same loads and generators in the same locations on a ship with the same number of zones. The ring bus is shown in Figure 3, and the breaker-and-a-half topology is shown in Figure 4. Since the breaker-and-a-half schema connects all the converters to both the port and starboard buses using the cross-ties, we removed the redundant PCM-1A in each zone and the second DC-DC converter for the radar. This obviates the need for a PCM-2A, but requires that the major breakers in the cross-ties be automatic or controllable bus transfers. The PCM-2A is the switching equipment that connects vital loads to mulitple sources of power, typically via an automatic or controllable bus transfer.

These two topologies were run through the full program as described in Section II above. Hit locations were randomly generated for nine hundred locations at three radii; the same random list was applied to each topology.

A. Metrics

One goal of this modeling effort is to report the results of tradeoff studies using standard, repeatable metrics. At present, the metrics include weight, volume, fuel usage (efficiency), and vulnerability. Weight and volume are reported as total weight and volume for the system, and can be broken down into equipment types to more specifically detail the differences between the systems under study. In these examples, the weights and volumes reported cover the electrical distribution system including gas turbines, generators, converters, and main bus cabling. They include neither the in-zone cabling downstream of the PCM-1A nor the loads themselves, except for the motors.

Efficiency is portrayed as annual fuel usage. Specific fuel consumption of the engines is calculated at the power drawn for different operating conditions and fuel usage is summed over a typical year as described in Section II-B.

The survivability metric is presented as the mean and standard deviation of the survivability tier and the overall

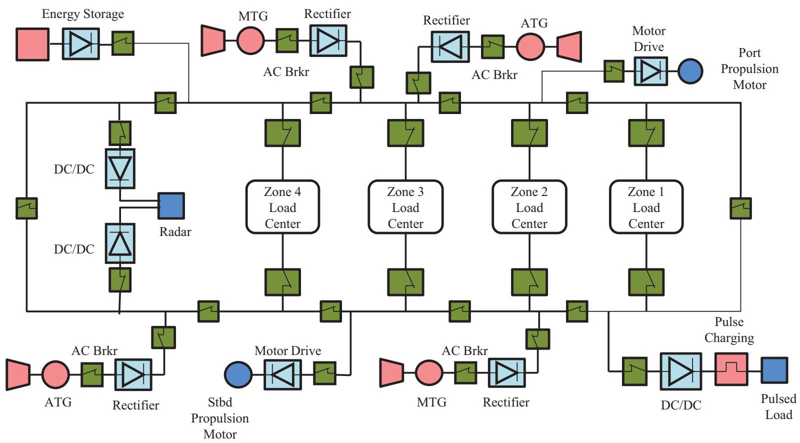

Fig. 2. ESRDC MVDC Baseline Topology

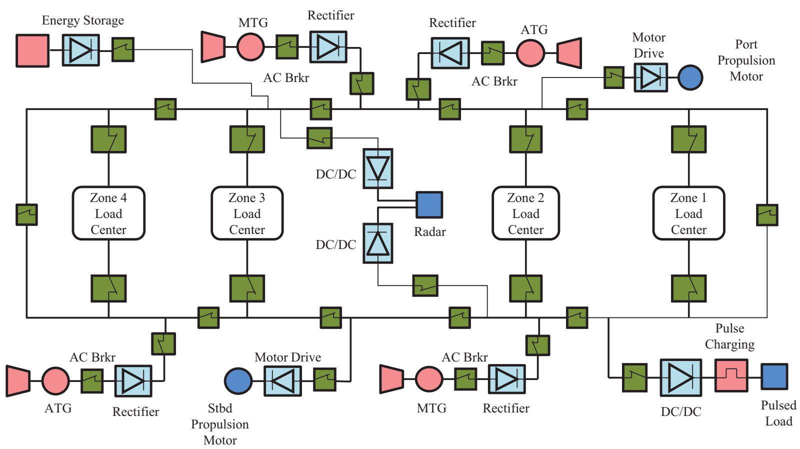

Fig. 3. MVDC Topology. This is modified from the ESRDC baseline to change radar location.

survivability score as described in Section II-C. Scores for both single- and double-hit scenarios are presented.

B. Results

Results are shown in Table III. Note that the breaker-and-a-half schema is lighter and takes up less volume, mainly due to the reduced number of PCMs. The annual fuel requirement is almost identical since the equipment layout and thus the losses are very similar. The breaker-and-a-half schema is less survivable, which may seem surprising at first, but the reduced redundancy in converters becomes evident here.

Viewing the breakdown of weight shown in Table III, note that the total PDM weight is much higher for the breaker-and-a-half schema, as is expected since there are significantly more breakers. We do not include any additional weight required for automatic switching or control systems; the weights we calculate are simply breaker weight. This increase in weight for the breakers is more than offset by the reduction in weight for the converters, as several converters are eliminated entirely. The bus weight is quite similar for the two schemata.

The losses for the two systems are quite similar. Since the power for each load must pass through a converter, and the converter types and efficiencies for the two schemata are the same, the PCM losses are equivalent. The PCM-1As for the zones are modularized such that the loading is kept within the more efficient bands of operation.

The detailed listing of survivability results in Table III shows that, for both the single- and double-hit analysis, the breaker-and-a-half topology has a slightly lower (worse) overall survivability score and a slightly higher (worse) survivability tier score. This means that on average, the ring bus system is able to power a higher weighted percentage of overall loads than the breaker-and-a-half system, and that the highest priority load that cannot be filled in the ring bus system is less important (lower weight) than the highest priority load that cannot be filled in the breaker-and-a-half system.

In addition, the standard deviation for the breaker-and-a-half survivability scores is higher than the standard deviation for the ring bus survivability scores, indicating more volatility.

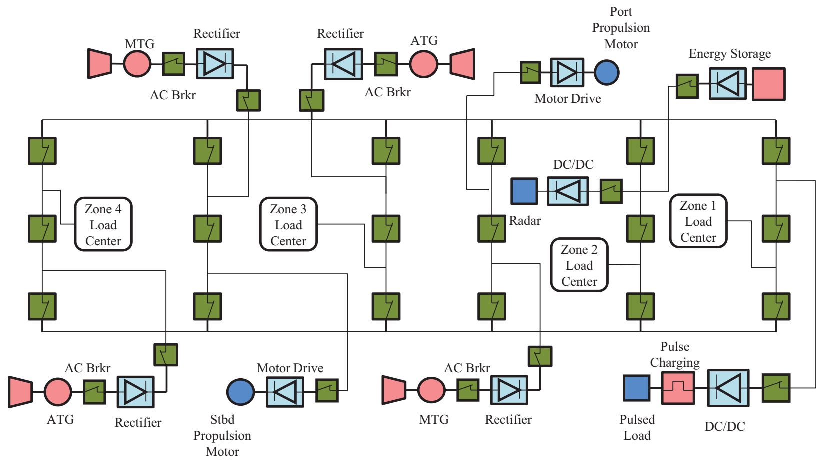

Fig. 4. Breaker-and-a-Half Topology

TABLE III
TRADEOFF STUDY RESULTS

	Ring Bus	Breaker and a Half
Total Weight (lton)	792	693
PDM Weight (lton)	29	42
BUS Weight (lton)	14	13
PCM Weight (lton)	246	134
Total Volume (ft^3)	42721	38527
Annual Fuel (lton)	16861	16805
Total Loss (kW)	3383	3382
PCM Loss (kW)	3374	3351
Bus Loss (kW)	9.0	6.8
Single-Hit Survivability		
Overall Surv Score Mean	98.34	97.17
Overall Surv Score Std. Dev.	6.21	9.75
Surv Tier Mean	8.39	9.05
Surv Tier Std. Dev.	2.43	3.81
Double-Hit Survivability		
Overall Surv Score Mean	91.25	86.47
Overall Surv Score Std. Dev.	16.19	22.61
Surv Tier Mean	10.40	12.05
Surv Tier Std. Dev.	5.87	6.87

V. CONCLUSIONS AND FUTURE WORK

We have further developed an architectural model for use in early-stage design to perform tradeoff studies using repeatable metrics. The model is modularized with an object-oriented class structure and an equipment library which makes implementation easier for the user. The addition of a GUI would ease setup of various scenarios to be analyzed.

The model now also incorporates a survivability analysis for single and multiple blasts, and performs an efficiency analysis over a range of operating conditions. Future planned work includes the addition of a cooling system design and analysis section. In addition, more work is planned on developing scaling relationships for sizing power electronics equipment, especially for the less-developed MVDC systems.

This model was applied to compare two possible topologies for an electrical distribution system: a ring bus and a breaker-and-a-half. It was found that the breaker-and-a-half was significantly lighter with less volume required, but was less resistant to damage. Due to the reduced weight, it may be worth investigating the breaker-and-a-half system in more detail to see if the slightly increased vulnerability can be mitigated.

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TABLE I
NOTIONAL SHIP LUMPED-PARAMETER LOADS

Zone	Num	Type	Vital	Cruise (kW)	Battle (kW)	Notes
1	1	DC	V	70	150	Constant impedance resistive
1	2	DC	V	0	615	Constant impedance resistive
1	3	AC	V	640	715	Constant impedance resistive
1	4	AC	V	390	400	450 Vac 3-phase resistive
1	5	AC	NV	275	910	450 Vac 3-phase constant impedance
1	6	AC	NV	7	0	120/208 AC load constant impedance
2	1	DC	NV	0	1	Lumped DC resistive
2	2	DC	V	20	75	Constant impedance resistive
2	3	AC	V	930	1400	Constant impedance resistive
2	4	AC	V	300	750	450 Vac 3-phase resistive
2	5	AC	NV	400	975	450 Vac 3-phase constant impedance
2	6	AC	NV	35	40	120/208 AC load constant impedance
3	1	DC	V	20	40	Constant impedance resistive
3	2	AC	V	1200	1200	Constant impedance resistive
3	3	AC	V	550	1900	Constant impedance resistive
3	4	AC	NV	375	750	450 Vac 3-phase resistive
3	5	AC	NV	4	0	450 Vac 3-phase constant impedance
4	1	DC	V	0	60	Constant impedance resistive
4	2	AC	V	200	480	Constant impedance resistive
4	3	AC	V	415	1750	450 Vac 3-phase resistive
4	4	AC	NV	220	675	450 Vac 3-phase constant impedance
4	5	AC	NV	4	0	120/208 AC constant impedance
Radar		DC	V	2850	3750	DC constant impedance
Pulse		DC	V	0	10000	