Study of Parallel AC and DC Electrical Distribution in the All-Electric Ship

Keywords: Electric-Drive Ship, MVDC, Electrical Distribution

Abstract

Medium-voltage DC electrical distribution is envisioned as a possible system for the warship of the future, bringing numerous advantages including a very power-dense architecture. This system takes the AC power produced by generators, immediately rectifies all power to DC and distributes it throughout the ship, requiring inversion back to AC for all AC loads. The question then arises whether it makes sense instead to route two parallel buses: an AC bus for all 60 Hz. AC loads and a DC bus to service all other loads. We model these two theoretical distribution systems in a notional destroyer using a preliminary design tool under development in our laboratory and find that the two-bus system is more efficient and lighter.

1. INTRODUCTION

The U.S. Navy warship of the future is envisioned to have extremely power-intensive weapon and sensing capabilities including such concepts as rail gun, laser weapons, improved radar, and integrated communications. This significant increase in ship service power requirements is shifting the balance between propulsion and service power. On DD 963 class ships of the 1970's, service power was approximately ten percent of propulsion power; on the DDG 1000, currently being built, service power is approximately one third of propulsion power; on the notional warship of the future, service power will be equal to or greater than propulsion power [Doerry, 2007]. One proposed method of achieving such power requirements is the Integrated Power System (IPS), which, through making use of electric-drive, provides the flexibility to produce power anyplace in the ship and decide whether to use that power for service or propulsion loads. This facilitates a ship with lower installed power if the ship is designed to trade maximum speed for maximum weapon and sensor load; in other words, the ship can use full radar and weapons capability or can go at maximum speed, but cannot do both simultaneously. This flexibility is more noteworthy when it is recognized that the power versus speed curve is roughly cubic; thus, reducing maximum speed by one knot can make upwards of 10MW of power available to other loads.

The Next-Generation IPS Roadmap [Doerry, 2007] presents a path of stepping stones to a power-dense system by proceeding through Medium Voltage AC, then High-Frequency AC, to Medium Voltage DC (MVDC) power distribution. The most difficult challenges lie in developing the MVDC system as it is the least mature technology. The Electric Ship Research and Development Consortium, of which MIT is a member, has worked toward solving many of the questions involved in implementing the steps described in the Roadmap.

In the currently envisioned implementation of MVDC distribution systems, power is generated as AC power, rectified to DC and distributed, then re-converted to AC for all AC zonal loads. This begs the question of whether the DC distribution system could be improved through a parallel AC distribution system to power only the 60 Hz. AC loads, thus avoiding the losses involved in converting from AC to DC and back. On a notional surface combatant of the future, the zonal AC loads are on the order of 5 to 10 MW as compared to the DC loads of approximately 100MW; however, the losses involved in converting even 5-10 MW of power may make a second bus worthwhile. This concept has also been discussed in [Leeb et al., 2010].

In this paper, we investigate the ramifications of these two power distribution systems in terms of efficiency, weight and volume. Initial observations of a parallel AC and DC distribution system are that efficiency is most likely improved, cable weight and volume will increase due to the second bus, and power conversion equipment weight and volume will likely decrease since less power must be converted. Additionally, construction labor costs will increase due to the installation of a second bus. Are the efficiency, weight and volume gains sufficient to offset the increased complexity and labor costs?

Our laboratory is involved in a body of work to develop an overall architectural model of an all-electric ship using a physics-based simulation 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 this paper we apply this design tool to compare a full DC distribution system to a parallel DC and AC distribution system.

This paper is arranged as follows. Section 2 gives background information on the notional ship. Section 3 describes the two distribution systems including individual components. The tradeoff study results are presented in Section 4. Conclusions and ideas for future work are presented in Section 5.

2. NOTIONAL SHIP

The notional ship is an electric-drive small surface combatant based upon SFI-2 as described in [Webster et al., 2007]. The vessel is an all-electric surface combatant of approximately 10,000 tons with two propulsion motors, advanced concept radar and pulse energy weapons installed. The side and plan views of the ship used in this paper are shown in Figure 1. These views show the hull, bulkheads, decks and machinery layout.

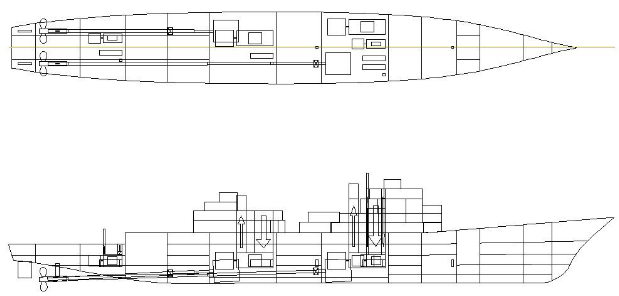

Figure 1. Notional ship with machinery spaces delineated.

The ship is divided into 4 zones for survivability purposes. Zonal divisions are located at watertight bulkheads, with at least one generator in each zone except Zone 1. Future research may investigate locating an energy storage device in Zone 1. Services are fed vertically to the superstructure from Zones 2 and 3.

In zonal design, the goal is for each zone to be as independent as possible; thus, there should be service generation capability and distribution within a zone. Connections between zones should be limited to cross-connects if possible. In the case of electrical distribution, only the main distribution buses cross the zone boundaries. Power conversion and further distribution is accomplished within each zone in accordance with the zonal electrical distribution system (ZEDS) of [Doerry, 2007].

3. ELECTRICAL DISTRIBUTION

Our model for the MVDC electrical distribution system is shown in Figure 2; we will refer to this as the MVDC system. The parallel DC and AC distribution system is shown in Figure 3; we will refer to this as the DC/AC system.

Electrical power is distributed using a ring bus architecture with isolation between each zone. Disconnect switches are also included forward and aft to enable split-plant operations. The two main power distribution buses are run on opposite sides of the ship, one on the second deck and one on the fourth deck, to obtain maximum separation for survivability purposes. The MVDC distribution system consists of a single ring bus. The DC/AC distribution system has two ring buses: the inner is AC and the outer DC.

Four major loads are fed directly from the DC bus via a dedicated converter: the radar, the high-energy weapon, and the port and starboard propulsion motors. All remaining loads are serviced by a zonal electrical distribution system (ZEDS). In the MVDC system, the power for all zonal loads comes from the DC bus and is converted by a PCM-1A to the required voltages and frequencies for further distribution within the zone. In the DC/AC distribution system, all zonal DC and 400 Hz. AC loads are serviced by the DC bus via PCM-1A converters, and all 60 Hz. AC loads are serviced by the AC bus via an AC to AC transformer to bring bus voltage down to 450VAC.

Since the majority of the power required is drawn from the DC bus, we optimize the system for DC distribution. Thus, power is generated at the equivalent of 10kV DC so only rectification and no subsequent step-up transformation is required in the DC bus. We assume for this simulation that power is generated at 60 Hz. AC. In the MVDC system, all power from the generators is immediately rectified to DC then routed in a single ring bus. In the DC/AC distribution system, most of the power is still immediately converted to DC and routed via the DC bus, but some power is directly routed in a parallel AC bus without initial transformation.

3.1. Loads

The electrical load requirements within each zone are drawn from the notional destroyer electric plant information provided to the Electric Ship Research and Development Consortium (ESRDC) by [BMT Syntek, 2003]. These in-zone loads are modeled as lumped parameters.

The four high-power loads are fed individually from the bus. The advanced-concept radar, located in the superstructure, is connected into Zones 2 and 3 but is fed from only one zone at a time. Radar power is assumed to be 5 MW. The energy weapon, located in Zone 1, is assumed to require a steady state power load of 10 MW. One propulsion motor is located in each of Zones 2 and 3; propulsion power at maximum speed of 30 knots is 33 MW output by each motor. A summary of the power requirements are listed in table 1.

3.2. Power Generation Modules

The power generation modules (PGMs) for this vessel are gas turbine generator sets which produce 60 Hz. AC power. We selected two Rolls-Royce MT-30 generators [Rolls-Royce] and two General Electric LM500 generators [GE Marine]. These produce a total of 89.94 MW of power; thus the loads exceed generating capacity by 4%. To this must be added losses in the distribution system. When using maximum service power (including the radar and energy weapon along with all zonal loads), the ship can still exceed 29 knots, thus losing less than one knot off top speed. Specifics on these two engines and generators are summarized in Table 2. Note that the specifications given include an AC generator that produces 4160 VAC or 450VAC; in the future warship these generators would be replaced with ones that produce the equivalent of 10kVDC; however, size and weight scale with power

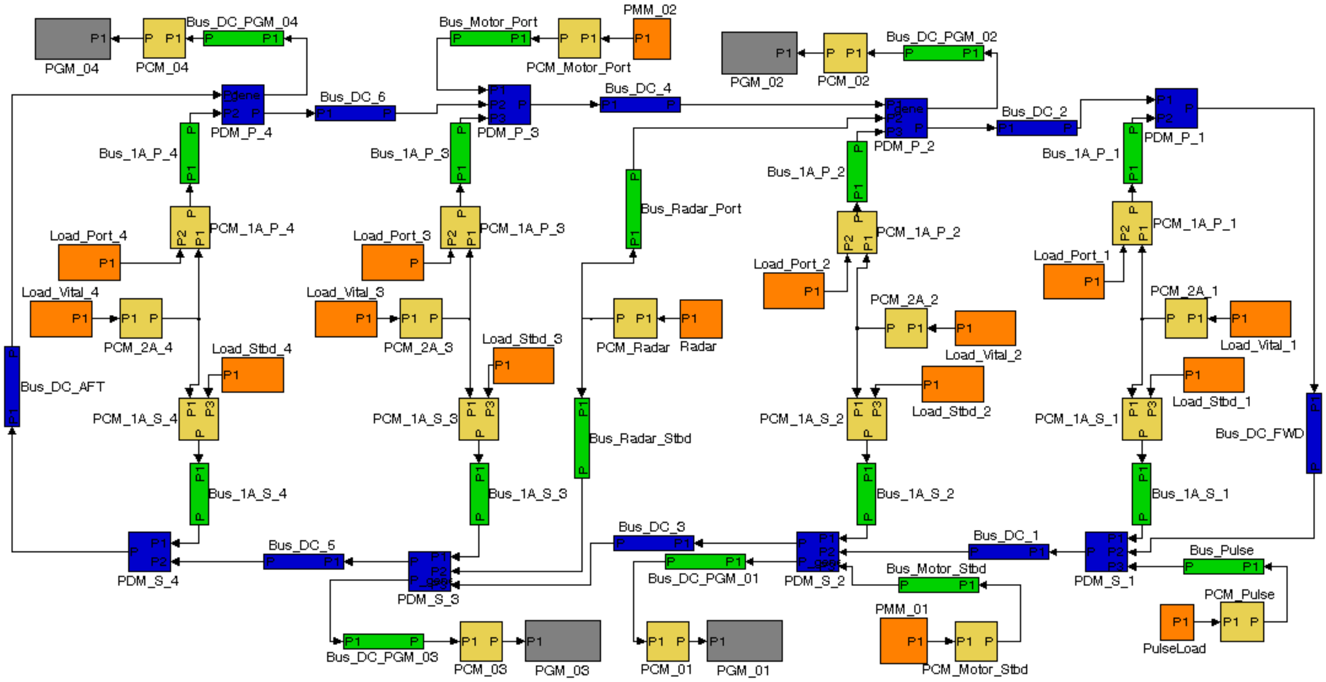

Figure 2. The MVDC electrical distribution system modeled in Simulink [MathWorks, 2010]. The ring bus architecture (Bus and PDM) connects generators (PGM) to zonal loads and bus-connected loads via power conversion modules (PCM). The ring bus components are dark.

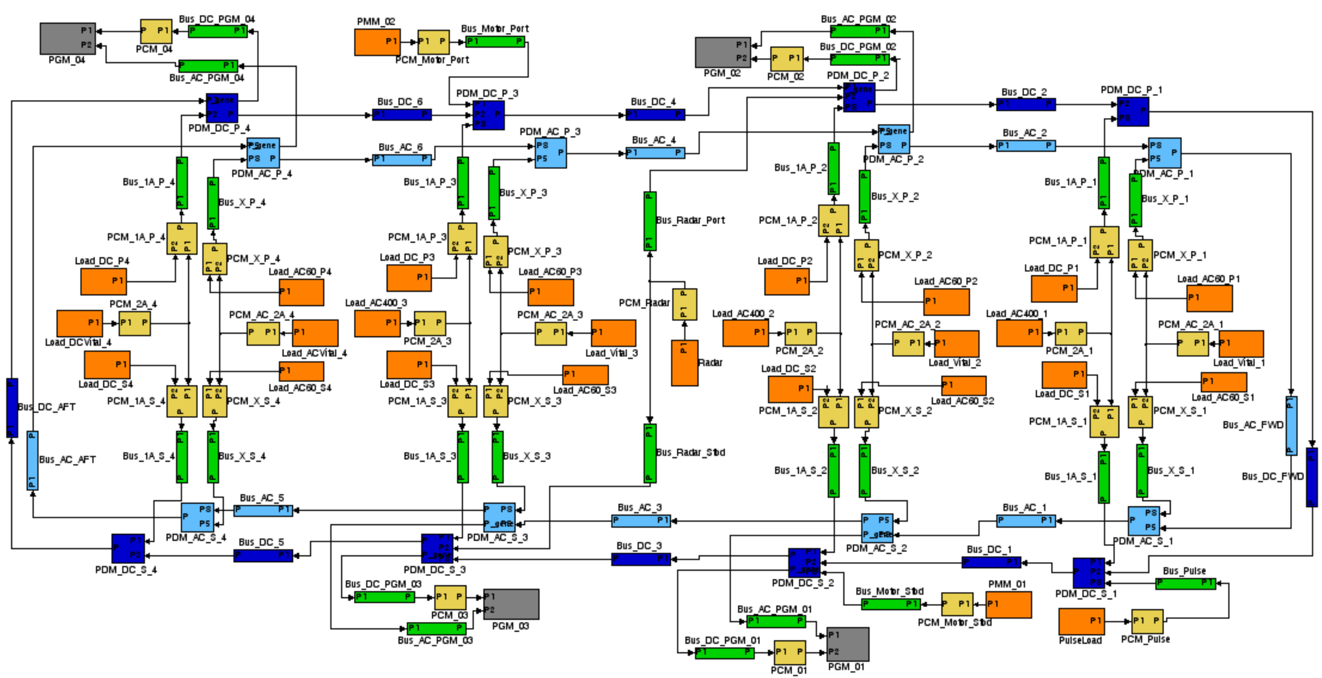

Figure 3. The DC/AC electrical distribution system modeled in Simulink [MathWorks, 2010]. The DC ring bus architecture connects generators (PGM) to zonal loads and bus-connected loads via power conversion modules (PCM). The AC ring bus architecture connects generators to AC zonal loads via transformers (PCM). The DC ring bus components are dark. The AC ring bus components are light.

Table 1. Maximum electrical load in kW by zone and power type

Zone	60 Hz AC	400 Hz AC	DC	Subtotal	Direct-fed DC	Total
1	1,970	55	765	2,790	10,000	12,790
2	3,161	4	76	3,241	38,000	41,241
3	3,834	16	40	3,890	33,000	36,890
4	2,898	7	60	2,965	0	2,965
Total	11,863	82	941	12,886	81,000	93,886

so the dimensions would remain approximately the same.

Table 2. Power Generation Module Equipment Data

Engine	MT-30	LM-500
Max Power (MW)	36	4.47
Weight (lton)	75.8	0.89
Volume (ft^3)	10,244	87
Peak SFC (lb/shp-hr)	0.345	0.440

3.3. Power Conversion Modules

Numerous types of power conversion modules (PCMs) are required throughout both systems. We provide a summary description first, then describe the modeling of each below; pertinent data is summarized in Table 3. Power is generated as 60 Hz. AC power then immediately rectified to DC (see Rectifiers below) for distribution in the DC bus. Four major DC loads are fed directly from this DC bus via a dedicated inverter/transformer (see Motor Drive below). Power for in-zone loads fed from the DC bus is converted to lower voltage DC or AC using a PCM-1A (see PCM-1A). Power for in-zone loads fed from the AC bus is transformed to lower voltage AC using a transformer (see Transformer). Loads that require an un-interrupted power supply are connected to both buses via a PCM-2A.

Rectifiers. The rectifiers used in this model are 12-pulse passive rectifiers as described in [Ouroua et al., 2007]. The 12-pulse rectifiers reduce harmonics induced in the generator and in any AC loads attached to that generator as compared to 6-pulse rectifiers; however, a phase-shifting transformer is required as well.

We use the same components in the DC/AC systems as in the MVDC system even though the DC power drawn is less, thus allowing the full generator power to be drawn as DC if required.

Motor Drive. Each of the four major DC loads has a dedicated inverter/transformer. In the case of the propulsion drive motors, we use SINAMICS medium-voltage variable frequency drives as described in [SINAMICS, 2008]. Since the PCMs for both the radar and the energy weapon are as yet unknown and since the PCMs do not change in the tradeoff simulations we run here, we use the SINAMICS Motor Drive as a placeholder of the appropriate power level for these PCMs. Note that the energy weapon is a pulse load; the associated PCM must include an energy storage device along with the required inverter/transformer. These PCMs are the same in both distribution systems as these loads receive their power from the DC bus in both cases.

PCM-1A. In the MVDC distribution system, the power for individual zonal loads passes through a PCM-1A [Doerry, 2007]. The PCM-1A is composed of three sections: the first converts the bus voltage to 1000V DC, the second produces various lower voltage levels of DC power, and the third produces lower voltage AC power, both 60 and 400 Hz. Each section is made up of multiple parallel modules which are hot-swappable, thus providing redundancy through the inclusion of one extra equivalent module in each section.

The DC power producing section is composed from Ship Service Converter Modules (SSCMs); the AC power producing section is composed from Ship Service Inverter Modules (SSIMs). In our simulation, we use 100kW SSCM modules and 90kW SSIM modules. Sizes and weights were obtained via [Wagner, 2009] and [SatCon Applied Technology]. It is thought that future development may produce modules of varying sizes such as 35kW, 100kW and 300kW [Doerry, 2007].

For the modules that accomplish the initial conversion from bus power to 1000VDC, we use the same power density and specific power as the SSCMs; since the conversion equipment is dominated by the filtering elements, the weight and volume scale with power more than with conversion ratio. The PCM-1A includes structural and cooling components in addition to the SSCMs and SSIMs; the weight and volume of these components were obtained via [Wagner, 2009] and [SatCon Applied Technology] as well. The water-cooled SSCMs and SSIMs have an efficiency of approximately 97%. The efficiency of the first conversion from bus voltage to 1000VDC is approximately 93%.

There are two PCM-1As per zone, one connected to each bus. Each PCM-1A must be capable of carrying half the load in the zone or all vital un-interruptible loads in the zone, whichever value is greater, with one SSCM and one SSIM out of commission. We designed standardized PCM-1As for Zones 2 through 4 which provide 2500kW of AC power and 200 kW of DC power. Zone 1 requires significantly more DC power than the other zones, so a separate PCM-1A was designed which increases DC power to 900 kW.

In the DC/AC distribution system, the size of the PCM-1A is significantly reduced due to the removal of the 60 Hz. AC load, which is the bulk of the zonal load. The resulting PCM-1As provide 90 kW of AC power for the 400 Hz. load and 200 kW of DC power. Again, the Zone 1 PCM has a greater DC load and therefore provides 90 kW AC and 900 kW DC.

Transformers. Since the generator produces power which is routed through the AC bus at high voltage, the AC power must be stepped down to 450VAC for zonal loads. This is achieved with an AC to AC transformer employed much as the PCM-1A is in the MVDC system; there are two transformers in each zone, separated laterally, vertically and longitudinally. The AC to AC transformer we use is modeled after those in [Federal Pacific], and is rated at 2500 kW.

PCM-2A. Vital loads that require un-interrupted power are connected via a PCM-2A to both zonal PCM-1As, and thus both buses. Since the PCM-2A is air-cooled, it has an efficiency of approximately 85%. In the parallel DC/AC distribution system, PCM-2As are connected to both PCM-1As and both AC transformers as required. These PCM-2As are smaller than those in the straight MVDC system.

3.4. Power Distribution Modules

The power distribution modules are switchboards that provide isolation for the bus connection cables and individual equipment. They are modeled as a collection of circuit breakers. We use the weight and dimensions of a Secheron UR26 DC circuit breaker, which is rated for 2600A at 3.6 kVDC. Although this voltage is too low for our application, the weight and size are representative. These breakers weigh 293 pounds and occupy 6.9 ft^3 each.

For the AC Bus circuit breakers, we use ABB ADVAC circuit breakers as described in [ABB]. These circuit breakers are rated up to 3000A continuous at 5-15kV, and weigh approximately 550 lbs each.

Within a zone, the two power distribution modules are separated longitudinally with at least one watertight bulkhead between them. Like the buses, they are vertically separated as well; those on the port side are on the second deck and those on the starboard side are on the fourth deck. In the DC/AC distribution system, a parallel set of AC power distribution modules are placed with the same survivability considerations.

3.5. Buses

The cables are modeled using armored and sheathed cable produced by General Cable. Main bus cable is single-conductor cable rated to 15kV with a 100% insulation level. In multi-cable runs, cable is spaced one diameter apart. Specifications of the cable used can be found in [General Cable] and are summarized in Table 4. Only I^2R losses are calculated. Cable length is calculated as Manhattan distance between equipment and distribution modules, thus allowing additional length for proper routing.

4. TRADEOFF STUDY RESULTS

Having modeled both systems in Simulink, we ran simulations and compared efficiency, weight and volume. Results are summarized in Table 5. As expected, the parallel DC/AC electrical distribution system is more efficient; it saves over 1400 kW in losses, a 33% reduction. Weight is reduced as well, by approximately 34 lton. Assuming the scaling assumptions we made to estimate equipment sizes are correct, volume is increased by approximately 3,000 ft^3. These numbers do not take into account the reduced fuel load required due to the improved efficiency, or the potential reduction in propulsion load due to the reduced drag of a lighter ship. In addition, it would make sense to reduce the size of the DC ring bus to the core required for major loads; this would further reduce losses, weight and volume in the DC/AC system.

We expect construction labor costs to be increased since a complete second bus would have to be run. The maintenance, training and spares costs may be higher as well since there will be additional equipment to maintain; however, the major additional pieces of equipment are AC to AC transformers and AC circuit breakers which are well established technology.

We expect survivability to be essentially unchanged since the AC bus is run alongside the DC bus. There will be additional bulkhead penetrations between zones for the AC bus.

5. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

We have presented a simulation of a medium-voltage DC electrical distribution system and contrasted it with an electrical distribution system that runs an AC distribution system parallel to the DC bus. We found that the combined DC/AC system is more efficient and lighter. We feel that the system has equivalent survivability as the straight MVDC system, with the penalty of increased installation costs and possibly increased training and maintenance costs.

One of the potential advantages of an MVDC distribution system with no associated AC bus is that the generators could be allowed to run at the most efficient speed of the gas turbine for any given load, since no particular frequency must be maintained for the bus. It would be interesting to reassess this study using fuel consumption values for the gas turbines running at their most efficient speed for each load. In this scenario the efficiency savings should remain the same, but the

Table 3. Power Conversion Module Equipment Data

Equipment	Max Power (MW)	Weight (lton)	Volume (ft^3)	Efficiency
40MW Rectifier/Converter	40	0.44	23.1	98%
5MW Rectifier/Converter	5	0.17	13.8	98%
SINAMICS Motor Drive	30	16.9	2340	99%
MVDC				
PCM-1A	2.72	15.3	370	90%
PCM-1A large (Zone 1)	3.42	19.0	415	90%
PCM-2A	0.54	7.5	190.2	85%
DC/AC				
PCM-1A	0.29	3.5	209	90%
PCM-1A large (Zone 1)	0.99	8.8	252	90%
AC Transformer	2.5		11	99.49%
PCM-2A	0.27	3.8	95.1	85%

Table 4. Cable Data

Cable	Voltage (kV)	Ampacity (A)	Number of cables	Weight (lb/ft)	Diameter (in)	Conductor Size (kcmil)	Number of conductors
Main DC Bus	15	848	6	4.6	2.257	777	1
LM500 DC Bus	15	536	1	2.7	1.818	373	1
MT30 DC Bus	15	848	5	4.6	2.257	777	1
Motor Bus	15	848	5	4.6	2.257	777	1
Radar Bus	15	536	2	2.7	1.818	373	1
Pulse Bus	15	754	3	4.0	2.123	646	1
PCM-1A Bus	15	536	1	2.7	1.818	373	1
Main AC Bus	15	378	3	1.8	1.526	222	1
LM500 AC Bus	15	528	1	11.3	3.720	535	3
MT30 AC Bus	15	378	3	1.8	1.526	222	1
Transformer Bus	15	432	1	10.0	3.545	444	3

Table 5. Tradeoff Study Results

	MVDC	DC/AC	Change
Total Loss (kW)	4347	2911	-1436
Total Loss (%)	4.6	3.1	-1.5
PCM Loss (kW)	4329	2895	-1434
Bus Loss (kW)	17.8	16.5	-1.3
Total Weight (lton)	425	390	-34
PCM Weight (lton)	232	187	-45
Bus Weight (lton)	39	50	11
Total Volume (ft^3)	36,172	39,190	3,018
PCM Volume (ft^3)	13,288	15,829	2,541
Bus Volume (ft^3)	2,221	2,699	478

fuel consumption should improve slightly for the MVDC system.

Another area of future research is to repeat the simulation under an operational scenario, thus testing the distribution system under a variety of loading schema and analyzing the results using a realistic employment of the ship to determine fuel savings over a typical year.

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