Cost Engineering a MVDC Power & Energy Design for Navy Surface Combatants

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Executive Summary

A critical decision for the future of Naval Power is, 'what is the primary power distribution that is cost effective to support future capabilities?' The decision for the Navy is often seen as medium voltage AC or medium voltage DC. However, "Medium Voltage" is not a specific voltage, and the actual decision is between alternating current and direct current for the primary electrical distribution. The decision is informed by the cost, energy conservation, ship design impacts, system reliability, and system functional performance.

Having successfully implemented 13.8kV Medium Voltage Alternating Current (MVAC) systems in existing ship classes, the Navy must consider the consequences of utilizing such systems in surface combatant designs that include high energy laser weapons, sensors, and other power-heavy loads. These systems do not require significant power when at rest or at sea but do carry significant power surge requirements when in operation for training or mission employment. All of these loads share a common feature of large transient power/energy demand. The dynamic nature of the loads associated with these capabilities can leverage energy storage to account for and buffer the sudden electrical pulses inherent in these loads. Theories suggest that a Medium Voltage Direct Current (MVDC) power system would provide power at greater efficiencies than an MVAC system, as well support integrated energy storage to provide on-demand energy for the anticipated future pulse loads. While qualitative and heuristic arguments have been made for why MVDC systems should be more affordable and energy efficient against an MVAC system, a comprehensive comparison and cost analysis that provides a quantitative rationale for these arguments has not been conducted. This paper is the first attempt to directly identify, describe, and compare these two architectures from a cost perspective.

Since maritime MVDC systems (those roughly in the 6-14kVDC range) do not exist, a quantitative algorithmic approach to develop a cost estimating relationship is not advisable. Therefore, this paper follows a heuristics approach to compare the theoretical costs of a MVDC to a MVAC architecture in a US Navy Ship. The components of each power system architecture are identified, described, and then compared to each other. Additionally, a qualitative risk assessment is made with regard to the ability to develop and produce the equipment necessary in a MVDC architecture. The primary uncertainty for a US Navy Ship mission power requirements, design sizing, and efficiency are not addressed in this paper.

The components required for a MVDC system do exist at some scale and technical level of maturity. However, there is nothing in production anywhere yet that would meet all the same requirements of a complete Navy surface combatant ship installation, nor is there commercial work being done to justify an investment from industry to support development of these components. While there may be savings in operation, maintenance, space, and weight, Navy would bear the entire cost of development and capital investment by industry to build these components. Due to the lack of quantifiable data and information regarding MVDC components, the US Navy would undertake significant risk and uncertainty in the pursuit of MVDC in surface ships.

Introduction

As the Navy transitions to a new era of electronic warfare, the ship power system becomes the critical foundation to support the future. Historically, the Navy relied on a 60Hz 450VAC power architecture to generate and distribute electrical power throughout the ship (Amy and Doerry, 2019). However, in recent years, combat systems and mission loads grew significantly and consumed the power margin that was inherent in traditional power generation and distribution designs. Compounding the problem, future combat capabilities will not only increase in power demand but also have to deal with increased power transients on the system. In an effort to address these challenges, the ZUMWALT (DDG 1000) class, MAKIN ISLAND (LHD 8), and future ARLIEGH BURKE (DDG 51) FLT III class introduced 4160VAC power to meet the needs of the modern loads (Amy and Doerry, 2019). For the future DDG(X) (shown as "Large Surface Combatant" starting in Fiscal Year 2030 (FY30) in Figure 1 and starting in FY33 in Figure 2), the Navy is planning to implement a 13.8kVAC system to support propulsion and have the flexibility to support future combat loads (Doerry, 2017). Additionally, Naval ship design mangers, systems engineers, and power and energy technical authorities anticipate the need for integrated energy storage and associated functionality in the future power system to support pulse weapons and stochastic loads. In an era of constrained budgets, the Navy needs to identify the most cost-effective means to support the needs of the future fleet.

Figure 1 Battle Force Procurement Plan, U.S. Navy 30-Year Ship Building Plan 2021

Fiscal Year	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
Aircraft Carrier							1				1				1				1				1				1			
Large Surface Combatant	2	2	2	2	2	1	1		1	2	1	1	1	1	2	3	3	3	2	3	2	2	2	2	2	2	2	2	2	2
Small Surface Combatant	1	3	3	4	4	3	2	2	2	2	3	2	3	2	3	1	3	2	3	3	3	2	3	2	3	2	3	2	3	2
Attack Submarines	2	2	2	3	3	2	2	3	2	2	2	3	2	3	3	3	3	3	3	3	2	3	3	2	3	3	2	3	3	2
Ballistic Missile Submarines			1		1	1	1	1	1	1	1	1	1	1																
Large Payload Submarine																					1			1			1			1
Amphibious Warfare Ships	2	2	2	4	3	2	2	3	2	2	3	3	3	4	4	1	2	1	1		1	4	2	2	3	3	2	2	3	3
Combat Logistics Force	1	3	3	4	4	2	3	3	3	3	3	3	4	2	2	4	1			1	2	3	3	4	4	4	4	2	3	2
Support Vessels	4	3	3	2	3	1	1						1		1													2	2	1
Total New Construction Plan	12	15	16	19	20	12	13	12	11	12	14	13	15	13	16	12	12	9	10	10	11	14	14	13	15	14	15	13	16	13

Figure 2 Battle Force Delivery Plan, U.S. Navy 30-Year Ship Building Plan 2021

Fiscal Year	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
Aircraft Carrier			1				1				1					1				1				1				1		
Large Surface Combatant	3	3	2	3	2	4	5	2	2	2		1		1	1	2	1	1	1	1	2	3	2	4	2	2	3	2	2	2
Small Surface Combatant	4	3	2		1	2	2	3	3	3	4	4	2	3	4	2	3	2	3	1	3	2	3	3	3	2	3	2	3	2
Attack Submarines	2	2	3	1	1	4	2	2	2	3	3	2	2	4	2	2	3	1	4	3	3	3	3	3	3	2	3	3	2	3
Ballistic Missile Submarines							1			1	1	1	1	1	1	1	1	1	1	1										
Large Payload Submarine																												1		
Amphibious Warfare Ships		1	1	2	3	3	4	3	3	2	2	3	2	4	3	3	4	1	2	1	1			4	3	2	2	4	2	2
Combat Logistics Force	1	2	1	1	1	5	3	3	3	4	3	3	3	3	3	3	3	3	1	1	2	1		3	2	4	4	4	4	4
Support Vessels	5	4	3	4	2	2	2	3	1	2								1		1										
Total	15	15	13	11	10	20	20	16	14	17	14	14	10	16	14	14	15	10	12	10	11	9	8	18	13	12	15	17	13	13

A critical decision for the future of Naval Power is, 'what is the primary power distribution that is cost effective to support future capabilities?' This Navy decision is often considered to be one between medium voltage alternating current (MVAC) or medium voltage direct current (MVDC). However, "Medium Voltage" is not a specific voltage but rather a broad range of voltages that are not consistent between AC and DC. Therefore, the actual decision is between AC and DC for the primary electrical power distribution. The decision between AC and DC is informed by the cost, energy conservation, ship design impacts, system reliability, and system functional performance.

While qualitative and heuristic arguments have been made for why MVDC systems should be more affordable and energy efficient than MVAC systems, a comprehensive feasibility and cost analysis has not been performed to date that provides quantitative rationale. The challenge with completing a comprehensive feasibility and cost analysis is that MVDC technology still requires significant investment in research, design, development, and production. The cost of that investment, in addition to theorized procurement costs, must be considered along with the estimated benefits. Even though the MVDC system have not been developed to the level to support a comprehensive feasibility study, the individual theories that accompany the MVDC system can be comprehensively evaluated.

The DDG(X) acquisition is anticipated to leverage a block upgrade approach with incremental updated every 5 years providing opportunities for upgrades to the power system in FY35, 40, 45, and 50 (Markle, 2020). If MVDC is required to support a future weapon system, then MVDC will either be integrated at the same time as, or in an acquisition block that precedes the weapon system block upgrade. The value over time of MVDC over MVAC will inform the priority and schedule for Science and Technology (S&T) and Research and Development (R&D) investments.

The purpose of this study is to present a quantitative cost comparison of MVDC and MVAC architectures based on an independent cost engineering approach. Additionally, the producibility risk associated with maritime MVDC components will be evaluated. This study will identify the parameters that will impact the cost of MVDC components, along with the uncertainty, and assumptions associated with those parameters; document the relative cost comparison to MVAC components; identify where industry investments in MVDC will support the development of Navy components; and identify factors that will impact the producibility of MVDC components and potential producibility risks.

The uncertainty in actual mission power requirements for future capabilities in Navy surface combatants, MVDC design hypothesis evaluation and ship design impacts, system reliability, energy efficiency, and system functional performance are not addressed in this paper.

Method

Since maritime MVDC systems (those roughly in the 6-14kVDC range) do not exist, a quantitative algorithmic approach to cost estimating is not feasible. Therefore, this paper follows a heuristics approach to compare the costs of a MVDC to a MVAC architecture in a US Navy Ship.

Initially, a review of existing literature on relevant MVDC maritime system architecture was conducted to compile a list of key hypothesis and associated assumptions that impact cost was generated from the literature. Subject Matter Experts (SMEs) on naval marine engineering and power systems were interviewed to identify and describe the components of generic, high-level MVAC and MVDC systems that would be typical for a U.S. Navy surface combatant. For the purposes of this comparison, “medium voltage” was defined as 12kV for both the surrogate AC and DC systems by the SMEs and assumed to meet all power and load requirements of the intended Navy platform.

Utilizing the cost factors identified from the literature review and following the architectures and use cases described by the SMEs, a comparison of MVDC and MVAC components was evaluated and documented. Specific or reference designs for either architecture were not provided. The analysis is solely focused on component-to-component comparison and ignores total numbers and arrangements of the components that may be required in a specific design.

Finally, risks associated with the research, design, development, and producibility of MVDC components were identified and documented to highlight the risk of uncertainty associated with cost comparisons between MVDC and MVAC systems.

The Uncertainty Assessment will consider the primary cost drivers for both MVDC and MVAC at the system level. Pulling from academic literature and readily available information from the commercial industry, the existence and availability of actual cost data for the primary cost drivers will be evaluated. The analysis will evaluate the cost data for each driver as related to the components discussed to determine the most appropriate cost estimating method to employ.

Since MVAC is still relatively new and MVDC architecture is not only a new concept but also depends on technology that is early in the research and development phase, the estimate will likely rely on analogies to existing systems or components that contain similar desired characteristics. These analogous systems and components will require assessment to determine adjustments to the cost estimate. Estimates relying on analogies generally contain a historically high uncertainty around the point estimate and will introduce significant risk using this method.

Should the research provide enough historical data from actual MVAC and MVDC systems or components that are somewhat similar in size, function, form, and scope to the 12kV range, then the cost analysis can employ the basis for a cost estimating relationship or a parametric measure. This will drive down the uncertainty around the estimate and the risk will certainly be reduced from an analogy method.

The producibility risk will be based on the evaluation of manufacturing risk categories for MVDC at a high level. Actual producibility risk evaluation is a rigorous and continuous process that is the responsibility of the program manager of the acquisition program. For the purposes of this study, readily available broad evidence and rationale on the industrial base will be evaluated to provide a basic assessment of low, moderate, or high risk for the manufacturing risk categories that comprise producibility risk.

Results

The following tables capture the findings of the literature review, SME working group, and commercial and industry research and present them in a consolidated comparison assessment for cost and uncertainty.

Quantitative Measures Summary

In lieu of cost data, an analysis of briefs, documents, and reports provided a heuristic comparison of the features and benefits of the MVDC to the MVAC based on the existing literature. Table 1 outlines the major system drivers and impacts to MVDC and MVAC ships, and largely summarized the prior discussion points. While all these systems may be directly or indirectly linked to a MVDC or MVAC system, they need to be evaluated for potential impact to the respective architecture of each system. An initial assessment of each component features or benefits is completed and indicates a likelihood of the advantage be either for MVDC or MVAC. The risk assigned to the feature or benefit was based on the maturity of MVDC and MVAC technology and whether the associated data to evaluate that feature or benefit would be known or unknown. Further cost and uncertainty analysis assessment of each component is required to determine the impact to the overall system cost to determine the cost advantage of one system over the other. The next step would be to assign costs and risks to each of the components in Table 1.

Table 1 *Quantitative Comparison between MVDC and MVAC systems*

System Trait	MVDC		Cost Advantage	MVAC	
	Feature or Benefit	Risk		Feature or Benefit	Risk
Major Components:					
Generator Set	Less Space/Weight	High	←	More Space/Weight	Low
Power Conversion Modules	Design Dependent	High	≈	Design Dependent	Low
Propulsion Motor	More Magnets	Low	→	Less Magnets	Low
Rectifiers/Inverters/ Transformers	Design Dependent	Moderate	≈	Design Dependent	Moderate
Energy Storage	Expect Less	Moderate	←	Expect More	Moderate
Cables/Bus Pipe	Expected Less Weight/Raw Material	High	←	Expected More Weight/Raw Material	High
Circuit Protection	More Space/Weight	High	→	Less Space/Weight	Low
Controls	More Complex	High	→	Less Complex	Moderate
Operations:					
Operating Costs (Manpower, sustaining support, and maintenance)	Expect Less	High	←	Expect more	Low
Fuel Cost	Expect Less	High	←	Expect more	Low
Thermal Efficiency	Expect More Efficient	Moderate	←	Expect Less Efficient	Low
Hardware Reliability (Mean Time Between Failure MTBR)	Assumed Same	High	≈	Assumed Same	Low
Major Commodities:					
Copper	Assume Less	High	←	Assume More	Low
Silicon Steel	Assume Less	High	←	Assume More	Low

Silicon Carbide	Assume More	High	→	Assume Less	Moderate
SWaP:					
Space	Expect Less	High	←	Expect more	Low
Weight	Expect Less	High	←	Expect more	Low
Power	Assumed Same	High	≈	Assumed Same	Low

Uncertainty Assessment

Any cost estimate study will carry with it some degree of uncertainty. The degree of that uncertainty is a function of the cost estimating approach and the availability, fidelity, and quality of the cost data used. While cost data was not available for this study, the uncertainty assessments made in Table 2 were based on the maturity of MVDC and MVAC technology whether the associated cost and demand data would be known or unknown.

Table 2 *Margin of Uncertainty for Cost Drivers*

	Range of Uncertainty	
Cost Drivers	MVDC	MVAC
Research and Development (R&D)	High	Low
Mean Time Between Failure (MTBF)	High	Low
Sustainment	High	Low
Operation	High	Low
Survivability	High	Low
Producibility	High	Low
Capability	Moderate	Low
Capacity	High	Low
Commercial Demand	Low	Low

Producibility Risk

Assessing producibility risk that includes producibility, quality, and manufacturing of a system is the responsibility of the program manager for the acquisition program. Producibility should be assessed at both the product and enterprise level and implemented as a continuous process throughout the life of the program. The limitations of this study only provide a very basic perspective of MVDC producibility from a high level. Because this assessment only considers basic knowledge and rationale of the industrial base and lacks fidelity, rigor, and advanced analysis, the producibility risk of MVAC is low across all nine of the manufacturing risk categories simply because industry has and continues to produce MVAC systems. Table 3 captures the risk assessment and associated rationale for each manufacturing risk category for MVDC.

Table 3 *MVDC Producibility Risk*

Manufacturing Risk Category	Risk	Rationale
Technology & Industrial Base	High	Unknown if significant investments are required due to lack of data for the requirements, design, and technology at the component and system level
Design	High	MVDC is not mature
Cost & Funding	High	Cost data does not exist; cost targets are not established
Materials	Moderate	Basic raw materials, components, subassemblies are known; accurate quantities are not known
Process Capability & Control	Low	Industry past performance to respond to new/unique Navy technology and design
Quality Management	Low	Industry past performance
Manufacturing Workforce (Engineering & Production)	Moderate	Skills, certs, requirements known; availability and capacity unknown
Facilities	High	Requirements for capabilities and capacities unknown
Manufacturing Management	Low	Industry past performance to respond to new/unique Navy technology and design

Discussion

Previous qualitative and heuristic hypotheses for the cost advantage of MVDC have lacked context and quantitative rationale. This study placed MVDC into a direct comparison with MVAC to produce a quantitative cost comparison, with an associated assessment of cost uncertainty and producibility risk. While not a comparison of actual system designs or even lists of analogous components, this study simply adds some level cost estimating rigor to previous theories that MVDC would be cheaper.

Although the actual power of a 12kVAC system does not equal that of a 12kVDC system, these voltages were provided as the definitions of MVAC and MVDC around which the cost engineering and producibility assessments were made.

The literature review revealed theories that in a size, weight, and power comparison (SWaP) of MVAC and MVDC of the same power, both the size and weight of MVDC would be less than that of MVAC and would therefore cost less. Further, theories highlighted reduced requirements for major cost driving commodities of copper and silicon steel in MVDC would produce additional cost advantages over MVAC. Finally, assumed improvements in fuel and thermal efficiency, reduction in fuel consumption requirements, and overall reduced operating costs would provide further cost advantage for MVDC over MVAC. However, a deeper dive into the literature, a review of readily available commercial information, and discussion with industry subject matter experts focused on the major components required in MVAC and MVDC provides caveats, context, and evidence on which to formulate a quantitative assessment of associated risk and range of cost uncertainty.

Table 1 captures the cost advantage assessment along with associated risk for the major components, total ownership cost, major commodities, and SWaP of MVDC and MVAC. A more detailed discussion of the cost of these system traits, organized by discussion at the major component level follows along with a synthesis of range of uncertainty for cost drivers and producibility risk for MVDC.

Power Generation and Conversion (Generator Sets & Power Conversion Modules (PCM))
Mechanical power is converted to electrical power in a generator. Both AC and DC generators rotate a conductor inside a stationary magnet. AC generators utilize continuous slip rings that provide alternating current while DC generators utilize a split-ring commutator that prevents the current from alternating. The gap in the split-ring commutator creates short circuits and the electrical current sparks across the gap placing increased wear and reduced performance in the DC generator as well as limiting the voltage.

DC generation enables the prime mover to operate more fuel efficiently. The frequency output of an AC generator is directly dependent on the rotational speed of the armature and must run at the designed output regardless of the load. Since DC systems immediately rectify the power, the rotational speed of the armature does not affect the output and the prime mover is able to run at reduced speeds when the electrical load is reduced, and higher speeds when the load is increased.

DC generators exist and are commercially available. However, these generators are rather small. For marine applications, they are typically rated in the 20-60kW range and targeted for use in cruising yachts and small commercial craft. Although a power range was not provided for this study and an actual design would drive the number of generators required, the 78MW power plant of the DDG-1000 class (produced by two main turbine AC generators and two auxiliary AC generators) provides a reliable point of reference to assume that DC generators would not be an option in an MVDC design. In fact, this assumption is so inculcated across both the Navy and the commercial SMEs interviewed, that the SME’s only consideration for DC power generation in a Navy ship design would be to implement AC generator sets that produce AC current, which would then be immediately converted to DC through a power conversion module.

A review of small, commercially available DC generators cost less than similar rated AC generators. An engineering build up should suggest that large DC generator should cost less than similar rated AC generators. While the initial cost of an analogous DC generator should be less than that of its AC counterpart, the wear and tear on the internal components, particularly the split-ring commutator and brushes, would likely incur increased maintenance costs. The ability to run the DC generator’s prime mover at variable speeds based on the load requirements will provide some fuel cost savings over an AC generator, but within the constraints of this study those savings cannot be evaluated. Any assumption about fuel savings carries with it a high range of uncertainty requiring addition systems analysis.

When considering the fact that DC generators do not exist in the power ratings required for a Navy ship, the theoretical comparison of associated costs between AC and DC generators becomes moot. No indications were found to assume that industry was pursuing the development of adequately sized DC generators. Therefore, Navy would solely incur all cost and risk associated with the pursuit of DC generators capable of producing MVDC.

The expected design for an MVDC system would be an AC generator with a power conversion module (PCM) that immediately converts the AC to DC. The addition of the PCM to the AC generator set would add cost to the MVDC power generation components. However, a PCM with a variable speed drive could take advantage of cost savings in fuel consumption if designed adequately with an appropriate prime mover that could operate as the electrical load dictates. In absence of specific designs to compare, a high level of uncertainty is associated with the acquisition and operation costs.

Power conversion module technology is mature at lower voltages for surface combatants and implemented in the DDG-1000 class design. Although PCMs in the power range required for an MVDC system of 12kV do exist and are commercially available, this technology is only mature for terrestrial applications. As DC current increases, the size, space, and internal air gaps required in the PCM construction increase exponentially. Terrestrial PCMs in this power range will not fit the size constraints of shipboard space. Nor are these PCMs built to ruggedized requirements for the pitch, roll, and vibration of a maritime environment let alone the Navy shock and survivability requirements. Significant investment would be required to advance the maturity of these components driving further uncertainty into PCM cost for MVDC.

Overall cost considerations for the prime mover in a power generator may include the RPM range, compression ratio, and overall number of cylinders or stages. While engineers have discussed a 25% reduction in weight per MW on an MVDC system compared to MVAC, that assumption is not clearly supported or documented. The metallic components of a prime mover, generator, and PCM need to be more understood to determine a measurable cost savings. Copper, silicon steel, and silicon carbide are some of the most prevalent and expensive cost drivers. The absence of a specific ship design that quantifies the actual size and number of these components required in the MVDC system further exasperates the degree of uncertainty associated with costing MVDC components that do not exist at a relevant level of technical maturity.

Propulsion Motor

The technology for both AC and DC electric propulsion motors is mature, deployed commercially and in naval applications, and continues to evolve as the maritime modality moves toward all electric designs. However, these motors do not operate in the 12kV range therefore both MVAC and MVDC designs would need to accommodate a step-down in the power provided. Either system could be designed to accommodate a motor that runs on AC or DC. At the component level, the cost of the AC motor would be less than the DC motor. While the majority of the materials and commodities required in the manufacture of AC and DC motors, DC motors require magnets driving up their relative cost.

Rectifiers/Inverters/Transformers

Rectifiers convert AC to DC whereas inverters convert DC to AC. Transformers step down or step up current. Rectifiers, inverters, and transformers will all be present in both MVAC and MVDC designs as required to accommodate different loads that will be integrated into the platform. One, two, or all three may serve as a subcomponent of a PCM within a specific ship design.

Rectifiers, inverters, and transformers have a significant range of design space. Within the constraints of this study, the cost of these components is considered roughly the same. A moderate level of uncertainty is assigned to that estimation. Specific design requirements and capability would need to be balanced with procurement and operational costs to reduce the uncertainty in the cost comparison. Interface standard requirements would also drive, inform, or even create trade space.

Energy Storage

Historically, energy storage in shipboard power distribution designs was implemented locally to protect equipment when power was lost. As combat and weapon systems evolve, their associated loads have become greater and more diverse in their waveforms. Integrating high power, pulsed, and stochastic loads can create untenable transients on the power distribution system. Implementing large energy storage can serve as one means to buffer these transients. MVDC literature indicates that a MVDC system should be able to manage power transients better than a MVAC system, but this study does not evaluate that theory. However, the requirement for large energy storage would not completely go away in an MVDC system.

Energy storage technology is still maturing. The same technology would likely be implemented in both MVDC and MVAC systems. MVDC literature suggests indicates that MVAC architectures would likely require more energy storage to handle the transients of complex combat systems loads. Based on this theory, the cost for energy storage in an MVDC system would be expected to less than an MVAC system. However, lack of specific platform design, expected loads, other factors that would drive specific energy storage technology decisions, and lack of experience with energy storage integrated into shipboard power distribution systems create a moderate level of uncertainty in the cost estimate for energy storage.

Cables/Bus Pipe

Both MVDC and MVAC systems will require some type of cabling for power distribution. In general, for cables in current production, a DC cable will use less material (such as copper), be easier to install and maintain, and be more efficient with less impedance and thermal loss. An AC cable is more complex with a three-phase, four-wire or a five-wire system, and more stringent safety standards for insulation.

In order to accommodate the 13.8kV MVAC system in the DDG-1000 class, Navy invested in the development of new cable types to meet the requirements of the ship. Cables suitable for the requirements of a naval 12kV DC or AC system will likely need to be developed. There are current research and development efforts that are pursuing alternative means of power distribution to traditional cables. These efforts include various investments into insulated bus pipe/bus bar and super conducting cables.

In theory, the cost of cables for an MVDC system should be less than that of an MVAC system. However, lack of an actual design or specific cabling requirements drive high risk into the cost estimate for both systems. The distribution of DC power introduces new engineering challenges that require additional non-recurring engineering (NRE) and would add further uncertainty. The constraints of this study limit the ability to evaluate the availability or technical maturity creating significant uncertainty in the cost estimation.

Circuit Protection
The primary component for circuit protection in a shipboard power distribution system is the circuit breaker. AC systems employ traditional breakers that use mechanical means to open a circuit as well as solid state circuit breakers (SSCB) that leverage semiconductors and advanced software algorithms to control power and interrupt the current. Since DC will arc over an open air-gap in a circuit, traditional DC breakers employ cooling, mechanical, or magnetic means to interrupt the current and extinguish the arc flash, but the current technology is limited to lower voltages. SSCB for DC circuits operate similar to AC SSCBs but are much more complex. In general, AC breaker technology remains relatively small as the size of the architecture increases. Conversely, as the size of a DC architecture increases, the size of the circuit breaker technology exponentially increases.

At the component level, the complexity and amount of raw material required for a MVDC breaker would drive a greater cost than the breaker required in a MVAC system. The technology for DC breakers is currently limited to the LVDC range. Evolving a DC system from the 1kV to 12kV range will require significant research and development in technology at the component level as well as at the system design level to ensure compliance with robust requirements of Navy shock and survivability standards. Circuit protection for MVDC likely carries the greatest risk and uncertainty of all the components evaluated within the constraints of this study.

Controls
In a component-to-component cost comparison, controls are especially difficult to evaluate as the actual design will dictate the controls required. Many decisions on the number and size of components, complexity of loads, level of integration, degree of survivability, etc. will affect the cost.

In general, controls and associated software differences between MVAC and MVDC architectures are not expected to be overly significant. However, survivability and zonal architecture requirements may drive a higher level of complexity in the controls for MVDC. Lack of specific design decisions and requirements add an increase of risk and uncertainty to the cost assessment for both MVAC and MVDC. Considering many of the MVDC components lack technical maturity, greater uncertainty and risk are assigned to the MVDC cost estimate.

Operations
The literature that advocates for MVDC not only provides theories on the cost benefits of acquiring an MVDC system but also the benefits of operating and sustaining MVDC systems over MVAC systems. The Office of the Secretary of Defense (OSD) provides clear guidance on the cost elements that make up Operations and Sustainment (O&S) costs. These elements include manpower, operations (primarily fuel), maintenance, sustaining support, and continuing systems improvements. Manpower, sustaining support, and continuing systems improvements are heavily dependent on actual system architectures, ship design, and acquisition strategies and therefore, fall well beyond the scope of this study. However, information on fuel use, the primary driver of operations cost, maintenance, and thermal efficiency, a driver of both fuel and maintenance costs, is readily available across the literature to provide the assessments captured in Table 1.

Small DC systems are more fuel efficient and thermal efficient than similar sized AC systems. Therefore, MVDC is expected to be more fuel and thermal efficient than MVAC systems. However, without actual MVDC components or systems to assess, high risk is associated with this assessment. While some literature suggests that MVDC may require less maintenance than MVAC, Navy designs and requirements would establish military standards (MIL-STDs) for mean time between failure (MTBF) or mean time between repair (MTBR). Threshold and objective requirements for MTBF are assumed to meet the same or similar MIL-STD for both MVDC and MVAC.

Uncertainty Assessment
The literature, along with working groups with SMEs, provided a consensus agreement on the high level, generic components that would be included in MVDC and MVAC architectures of the 12kV range. However, quantifiable metrics associated with the MVDC system required to support a cost estimate with a limited range of uncertainty do not exist, were not readily accessible, or limited in their utility. Since there are no maritime 12kVDC systems in existence, nor do most components required for such a system exist, actual costs do not exist to be able to complete estimates through analogy, engineering build-up, or parametric approaches.

Cost data for the DC system and components for the DDG-1000 class was not available for this study. Even if this data was available, the DC system would not provide a reliable base or cost floor or ceiling for several reasons. First, the DC system in DDG-1000 class is in the 1kVDC range vice the 12kV range. Second, the power distribution architecture of DDG-1000 class is a combination of DC and AC but the assumed architecture for this study is entirely DC. Similarly, the DC architecture of the DDG-1000 class lacks all or some quantity of the necessary components identified for the hypothetical MVDC system of this study. Finally, the acquisition strategy and limited number of ships in the class do not provide a reliable degree of uncertainty for cost estimations for any systems in the ship, let alone one that has yet to be developed.

Acquisition strategies and timelines, beyond the data provided in the 30 Year Ship Building Plan provided in Figure 1 and Figure 2, were not provided. The assumption was made that these variables would be consistent for both the MVDC and MVAC systems for the sake of this comparison.

The ability to adequately examine industry's capability and capacity to manufacture MVDC components was extremely constrained by the scope and level of effort of this study. Finding no clear commercial demand or requirement for MVDC components similar to those assumed in this MVDC architecture compounds the degree of uncertainty of industry's ability to meet a very unique Navy need. Further compounding this risk is the Navy's ability to maintain and sustain this industrial base. With no corresponding commercial market, MVDC components will be unique to the Navy and there is no evidence that Navy investment would drive commercial adoption of the MVDC systems. Analogous investment was made to reduce risk and maintain the marinized gas turbine industrial base. Even with strong commercial industrial bases in aviation and terrestrial power generation sectors and the trickle of new materials and designs into maritime gas turbines, the Navy still pays a premium to support the maintenance of the maritime gas turbine industrial base and the marinization of product line improvements.

Based on factors described above and highlighted in Table 2, the cost estimates for MVDC presented carry with them a high degree of uncertainty. While the literature indicates that the physical components and traits would be less in an MVDC system, that theory carries with it a high degree of uncertainty.

Since actual cost data was not available for either the MVDC or MVAC, especially for a Navy warship, actual cost analysis, either from an investment perspective (capital expenditures – CAPEX; for Navy RDT&E/OPN/SCN) or from an operational and sustainment perspective (operating expenses – OPEX; for Navy OMN) could not be conducted to a reasonable degree to conclude that one system is less costly than the other. Instead, general comparisons were made between the two architectures and considered the major components and their actual or perceived primary cost drivers. While any cost estimate will have an associated level of uncertainty directly tied to the fidelity of the data analyzed, the constraints and limitations of this study provided no cost data and little fidelity in data or information available to make strong cost comparisons. However, the range of uncertainty can be quantified in relative terms.

As summarized in Table 2, a range of uncertainty for the primary cost drivers can be quantified in the relative terms of low, moderate, or high range of uncertainty. The Navy acquired and deployed 13.8kVAC systems in multiple platforms. Maritime and more robust naval AC systems are mature, well understood, and ubiquitous. Cost data for the major cost drivers indicated exists, should be available to some degree, and will provide enough fidelity to provide a low range of uncertainty in any assumptions made with regard to cost. Considering that many of the components required in an MVDC lack technical maturity and maritime DC systems overall have a relatively small history in practical application and production, the availability of cost data is assumed to be extremely limited. Significant non-recurring development costs at the component and system level for DC systems in general and MVDC more specifically have yet to be realized and can significantly contribute to the total cost of MVDC. As such, the range of uncertainty for the cost of MVDC is high. The high range for uncertainty for R&D and the level of MVDC technical maturity drive the high range of uncertainty for the cost of maintenance (MTBF), sustainment, operation, survivability, producibility. Because this study revealed very little to no commercial interest in pursuing MVDC in the maritime modality, the range of uncertainty for commercial demand is assumed to be low further compounding the range of uncertainty for the cost of production capacity.

Producibility Risk
Producibility is an assessment of the relative ease of manufacturing and should be performed by the program manager at both the product and enterprise level. Producibility is a design accomplishment that should be established as a Technical Performance Measure (TPM) for a program of record. This study evaluated a theoretical MVDC system that includes components that do not exist or only exist at low Technology Readiness Levels (TRL). A true producibility risk assessment is not possible. However, Table 3 describes a heuristics approach to assess the producibility of the theoretical MVDC system based on the general knowns and unknowns of the industrial base and the ability to respond to Navy requirements.

Considering MVDC technology is not mature, data for the requirements, design, and technology at the component and system level are unknown. As such, this study is unable to evaluate if significant capital investments into the technology and industrial base are required. Also related to the overall immature level technology is the potential to assess industry's ability to produce a manufacturing design that meets Navy standards and requirements. As discussed throughout this study, cost data is limited or does not exist at all for much of the technology required in a MVDC system, nor have cost targets for Navy acquisition been provided or even discussed. For these reasons discussed, high risk is assigned to the technology & industrial base, design, and cost & funding manufacturing risk categories.

Although the MVDC technology is not mature, the basic raw materials, components, and subassemblies are generally known. However, they might not be well understood across the system nor are accurate assessments available for the quantities and standards required. As such, the risk for materials required to manufacture an MVDC system is at least moderate.

Industry has demonstrated the ability to respond to new and unique Navy technology and design to produce and deliver new and advanced systems, architectures, and capabilities. Recent examples include the DDG-1000 class destroyer and littoral combat ship classes. Based on this track record, the risk for industry's process capability & control, quality management, and manufacturing management is assessed as low. However, while the skills, certifications, and other workforce requirements may be known, the required availability and capacity of the workforce is not known or even assessable without an acquisition strategy to evaluate against and a clear understanding of skills or certifications required for immature technologies. Therefore, the workforce risk is at least moderate. Finally, due to lack of requirements for manufacturing capabilities and capacities, high risk is associated with facilities required to produce MVDC systems.

Conclusion

As the Navy evolves from long proven and traditional power generation and distribution systems in surface combatants to those that can accommodate the ever-increasing load demand and considerable surge power required and associated transients, cost effective means to support these future needs must be identified. In theory, an MVDC distribution system has three benefits: support for these advanced electrical loads, reduced space and weight demands in the surface platform, and improved energy efficiency. However, the cost to acquire a MVDC system compared to a power equivalent MVAC system is fundamental when considering those theoretical benefits. Previous analysis comparing MVAC and MVDC systems have struggled to develop cost estimates for a MVDC system, which has limited the utility of the analysis with respect to clear, objective conclusions.

The goal of this study was to determine if a MVDC system would be cheaper than a MVAC system for Navy ships and to provide some assessment of the producibility risk associated with the acquisition of a MVDC system. While the analysis conducted may seem to suggest that the components of a MVDC system have the potential to be cheaper, the lack of actual cost data associated with these components places the highest degree of uncertainty on that assessment. This study did reveal that specific designs, which could be heavily influenced by competing decision points, add more uncertainty to the cost assessment. This degree of uncertainty is further compounded when considering that costs to develop the MVDC components and build associated infrastructure to produce them have yet to be realized. This study was limited in the ability to adequately assess the manufacturing capabilities of existing industry vendors and their capacity to produce MVDC components. In absence of close engagement with industry, producibility risk should be considered critical.

While the components required for a MVDC system do exist at some scale and technical level of maturity, there is nothing in production anywhere yet that would meet all the same requirements of a complete Navy surface combatant ship installation. There is no commercial work being done to justify an investment from industry to support development of these components. While there may be savings in operation, maintenance, space, and weight, Navy would bear the entire cost of development and capital investment by industry to build these components. Due to the lack of quantifiable data and information with regard to MVDC components and no viable commercial market, Navy would undertake significant risk and uncertainty in the pursuit of MVDC.

Recommendations for Follow-on MVDC Cost Analysis

Acquiring accurate cost data for existing MVDC and MVAC systems is critical for a quantitative comparison between the two architectures. Cost data for a similar system could be applied based on the similarities and differences to a proposed Naval system producing an estimate with the greatest degree of uncertainty. Cost data for three or more DC systems spread across a range of power (kV) could be used to develop a parametric cost model and the proposed Naval system could be projected on that continuum with a significant degree of uncertainty. An engineering build-up could be developed from a list of components with associated costs to produce an estimate with some degree of uncertainty. Finally, if actual costs for the proposed Naval system were available, the estimate with the least amount of uncertainty could be developed for the future system.

However, as indicated several times throughout this paper, actual components for a maritime MVDC system do not exist. Components for maritime DC systems in general are limited and the associated cost data is difficult to obtain. Without actual cost data for DC systems, any analysis will carry with it a significant degree of uncertainty. Knowing that these systems do not exist and require investment to be developed and then produced add significant risk to that uncertainty for any method used to determine the cost of a Naval MVDC system.

Engineering Build-up Approach

Low voltage DC (LVDC) systems do exist and are in development for the maritime sector. A future study that examined a specified engineering design for a nominally 1kVDC system could yield a high-fidelity cost estimate for a maritime electrical generation and distribution system. Such a study could be used to produce a lower limit for an MVDC system with uncertainty. From there, a design analogous to deployed 13.8kVAC systems could provide an extrapolated cost estimate to compare to the nominally 1kVDC system. However, this estimate will contain considerable risk since the scale of the two systems is more than 10-fold.

Qualitative Benefits Ranking

In lieu of cost data, a qualitative method could be used to determine if one system has some trait or value that would exceed any cost associated with its acquisition. Comparing the qualitative benefits of an MVDC system to an MVAC system provides a non-cost analysis that will indicate if one system has an intrinsic value that may exceed a cost detriment. If one system has a cost advantage and the other system has a benefit advantage, then the analysis provides the means to determine the intrinsic value of the benefit.

A Qualitative Benefits Ranking, similar to that described by the Department of the Navy Economic Analysis Guide published by the Naval Center for Cost Analysis (NCCA), could be used to rank and weigh the comparative benefits of MVDC and MVAC architectures. In the model produced from this method, costs are the inputs and the benefits, and what the Navy receives from the system are the outputs. Costs and benefits are mutually exclusive, and therefore considered separately to avoid any double counting such that a benefit cannot be that one system costs less than the other.

The Qualitative Benefits Ranking will require significant involvement by SMEs of both MVDC and MVAC system architecture as well as Navy operators. SME input and analysis are integral to determine benefit weights, scores, and rankings. Such input also poses risk of personal biases and motivations, or authority, personality or reputation dominating and unduly influencing the outcome. Therefore, the Delphi Technique, developed by RAND early in the Cold War and continually used and further developed since, should be used to develop the benefits weights, scores, and rankings. Through multiple rounds of questionaries in a recursive manner that share the initial results, the Delphi Technique should reduce the risks and allow free expression of opinions, open critique, and revision of earlier judgements leading to authentic consensus among the group of SMEs.

Additionally, qualitative benefits ranking can be challenging for marine engineering systems. Many of the design parameters are nonlinear and coupled making the determination of the weighting parameters challenging. Generally, the best approach with Naval Platforms is to develop synthesized concepts to compare alternative marine engineering architectures. By developing a synthesized concept, the coupled variable impacts and the inherent nonlinear system dependencies are accounted for. Finally, limit the qualitative benefits ranking to inform small one-for-one trades in marine systems decisions and defer larger system-wide trades for ship concept studies.

Table 4 is a proposed Benefit Matrix used to measure and compare the qualitative benefits of an MVDC and MVAC system. Table 4 is provided for discussion and example purposes only. The actual matrix used in follow-on work should be developed and completed by the researchers that structure the study and with the input from the SMEs.

Table 4 - *Proposed Qualitative Benefit Matrix for MVDC/MVAC Comparison*

Benefit	**Weight**	**MVDC**		**MVAC**	
		Score	**Wtd. Score**	**Score**	**Wtd. Score**
Hardware Consideration					
Operations Consideration					
Weight Consideration					
Space Consideration					
Efficiency of Systems					
Heat Consideration					
Manpower Consideration					
Mission Readiness					
Safety Security					
Meeting Standards					
Totals					

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