Architecture Choice

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1. Introduction

An architecture defines patterns for how the elements of a system can connect and interact. Most shipboard electrical power systems can be classified as radial architectures, ring architectures, or zonal architectures. Shipboard propulsion architectures are usually classified as mechanical drive (MD), hybrid electric drive (HED), integrated power systems (IPS), and electric drive (ED). The open question is which architecture should be chosen for a particular ship design. The answer of course, is the architecture that best meets all the customer requirements. This solution however, requires a definition of the customer requirements, a definition of what is meant by "best," and a means for evaluating whether architectures meet these criteria.

Ship design is generally broken into three phases: concept design, preliminary – contract design, and detail design. The products of concept design are a set of requirements, an evaluation of the mission effectiveness of a ship that meets the requirements, and estimated acquisition and life cycle costs. The product of preliminary – contract design is a shipbuilding specification which is part of the contract between the customer and shipbuilder. Finally, the products of detail design are all the design and engineering artifacts required to construct, test, and certify the ship.

During concept design, one should not strive to choose an architecture; rather one should identify architectures for elimination that are likely not feasible or are highly dominated by other architectures. An architecture is dominated by another architecture if the other architecture is feasible and better in every metric of importance. Choosing an architecture is usually not necessary in producing the products of concept design; keeping multiple feasible architectures is desirable. Multiple feasible ship configurations that are evaluated to meet the set of requirements should be used to establish the estimated acquisition and life cycle costs; these costs cannot be directly estimated from the set of requirements.

In concept design, eliminating architectures is equivalent to not considering ship configurations employing the architecture when establishing estimates for acquisition and life cycle costs. The "best" architecture is generally not determined, largely because the level of analysis performed during concept design is usually not sufficient to determine which is "best." The definition of "best" may even evolve during the course of the concept design.

An architecture is typically chosen during Preliminary-Contract design and reflected in the shipbuilding specification. The choice should be based on a comprehensive trade-study that is detailed sufficiently to determine the "best" architecture. Often the criteria for "best" includes lowest cost and lowest risk while still meeting all requirements. Commonality with other ships in the fleet may also be part of the "best" assessment. In some cases, the trade studies may not be able to differentiate among two or more architectures; in these cases, the choice of architecture may be left to the shipbuilder as part of detail design.

If the decision is left to the shipbuilder in detail design, the "best" architecture determination may include an evaluation of how easily or difficult the architecture is integrated into the shipyard's standard work practices.

The "best" architecture may hinge on a capability uniquely enabled by one architecture. Understanding the opportunities offered by each architecture and how to exploit these opportunities to maximize effectiveness can be very valuable in identifying the "best" architecture. There is not a simple flow chart where one is led through a few decision blocks to the preferred architecture; requirements, opportunities, and limitations can all interact in novel ways during the design process.

The discussion so far has centered on "clean sheet" designs. Many ship designs however, are either modified repeats of an existing design, or the conversion of an existing ship. In these cases, if the original architecture is feasible, even if suboptimal for the new set of requirements, it will likely remain. The installation of a new architecture is generally only considered if the original design has an architecture that will no longer work. For example, if the original design has an architecture based on low voltage power generation and the new design must support significantly higher loads, then it makes sense to explore architectures with medium voltage power generation in case the loads grow so much as to make the low voltage power generation architecture infeasible.

This document provides some of the insights needed to make a good electrical power system and a good propulsion system architecture choice. See McCoy (2015) for additional insights.

2. Electrical System Architectures

Most commercial ships and many international naval ships employ a radial distribution system with two or three generator switchboards. Two of the generator switchboards are configured for normal operation, and the possible third switchboard configured as an emergency switchboard powered by an energy generator set and a connection to one of the other switchboards; all the emergency loads are connected to the emergency switchboards. With basic SOLAS survivability requirements, the majority of PGMs and the two generator switchboards for normal operation are either co-located, or very near each other; only the emergency generator and switchboard is located some distance away. In commercial ships, very few loads require normal and alternate sources of power.

For ships with greater survivability requirements, such as naval ships, ring buses can be commonly found. The generator switchboards are spread out across the ship such that damage from non-overmatching threats will result in only the loss of a single switchboard. Normal and alternate sources of power are provided to mission critical loads (including emergency loads) via feeder cables from multiple switchboards on the ring bus. A dedicated emergency switchboard is not provided; at least two PGMs on different switchboards should have the capability to serve as an emergency generator. For non-IPS ships, three generator switchboards, each with one PGM, connected in a ring bus is a common configuration; each PGM has a rating sufficient to power all critical loads on the ship and two PGMs can power the maximum margined ship service load.

Larger ships, generally those with a length greater than about 100 m, with greater survivability requirements, or with a large number of critical loads requiring two sources of power, may find a zonal distribution system to be most economical and effective. In a zonal distribution system, the normal and alternate feeder cables to critical loads largely run athwartship; in a radial or ring distribution system, the normal and alternate feeder cables largely run fore and aft and are significantly longer. Consequently, the weight associated with feeder cables can be significantly less in a zonal system as compared to a radial or ring distribution system.

Zonal systems that implement zonal survivability reduce overall system complexity by limiting electrical system impacts to damaged zones. Note that the number of zones, and the zone boundaries should be established at the total ship level and should be identical for all distributed systems. Implementing zonal survivability is facilitated if the total number of zones is between five and seven.

Commercial passenger ships that are required by SOLAS to have a Safe Return to Port capability should also consider a zonal architecture.

2.1. Selecting Medium Voltage vs Low Voltage

The total electrical load estimate is needed to determine whether power generation should be medium voltage or low voltage. Generally, if the maximum load flow anywhere in the ship exceeds 4000 amps assuming a 0.8 power factor and the highest standard low voltage nominal system voltage, a medium voltage system should be used. Circuit breakers typically are readily available up to 4000 amps; higher rating circuit breakers are available on special order with a substantial cost premium. For U.S. naval ships, the standard low voltage ac voltage is 450 VAC line-to-line which corresponds to an apparent power flow of 3.1 MVA or 2.5 MW at 0.8 PF. Since split plant operation is always a possibility, if the maximum margined ship service load with service life allowance is less than 5 MW (2 times 2.5 MW), a low voltage system is likely to be less expensive and more power dense than a medium voltage system; the maximum load flow in the system, converted to current, should be less than 4000 amps. Between 5 MW and 10 MW a limiting load flow or load flow analysis (Doerry 2025) should be conducted to determine the worst-case load flow at low voltage. If the worst-case load flow, converted to current, is close to or greater than 4000 amps, then a medium voltage solution is warranted. For a total load above 10 MW, a medium voltage solution is likely to be the “best.”

2.2. Selecting AC or DC

If a low voltage solution is appropriate, diesel engines are anticipated to be prime movers under endurance conditions, and fuel efficiency is important, then generating power at 1 KV dc should be considered. Similarly, if a low voltage solution is appropriate and fuel cells, centralized energy storage, high power quality and quality of service requirements, or high ramp rate loads are anticipated, then a 1 kV dc system should be considered. AC should always be considered if a low voltage solution is appropriate.

If a medium voltage system is appropriate, an ac system should always be considered. If diesel engine prime movers, fuel cells, centralized energy storage, high power quality and quality of service requirements, or high ramp rate loads are anticipated, then a MVDC system should be considered. Note that an MVDC system may only be appropriate if the acquisition program is willing to mature equipment prototypes to production units and conduct system level integration testing prior to ship installation.

2.3. Selecting nominal system voltages

The nominal system voltage should be selected based on standard voltages and the availability of appropriate circuit breakers. For U.S. naval ships, the standard low voltage ac distribution voltage is 450 volts (with 440 volt utilization voltage) as defined in MIL-STD-1399-300-1. At this time, there isn't a standard low voltage dc distribution voltage, although 1 kV is used on the DDG 1000 class of destroyers. For medium voltage applications, MIL-STD-1399-300-2 defines three standard ac voltages: 4.16 kV, 6.6 kV and 13.8 kV. The U.S. Navy has not established a standard for MVDC power.

IEEE 45.1 establishes the following standard ac low voltage nominal system voltages: 120, 208, 230, 240, 400, 450, 480, 600, and 690 volts. The standard ac medium voltage nominal system voltages are: 3.3 kV, 4.16 kV, 6.6 kV, 11 kV and 13.8 kV. The standard dc low voltage nominal system voltages are: 110, 220, 375, 600, 650, 700, 750, and 1000 volts. The standard dc medium voltage nominal system voltages are: 1.5 kV, 3 kV, 6 kV, 12 kV, 18 kV, 24 kV and 30 kV. The customer will often specify the low voltage ac nominal system voltage based on maximizing commonality of equipment with other ships the customer owns.

For medium voltage applications, the voltage is typically chosen to be the lowest standard nominal system voltage that will result in the highest current rating for a circuit breaker to fall between 1000 amps and 3000 amps (possibly 4000 amps for MVDC). For medium voltage applications, higher voltages generally require greater volume for creepage and clearance, but the conductor size of cables is reduced. AC circuit breakers are generally available with ratings up to 3000 amps. For MVDC applications, high current circuit breakers are not currently commercially available; prototypes exist with a rating of 2000 amps and circuit breaker designs exist for a rating of 4000 amps; a 3000 amp breaker should be feasible.

If the ship is intended to employ shore power (shore-to-ship power) while inport, consideration should be given to using the standard voltage (and frequency) for the shore power available in the intended operating ports. Using the same voltage can simplify the shore power connection.

3. Propulsion System Architecture

The propulsion system architecture is heavily influenced by sustained speed (service speed) and endurance requirements. Many commercial ships normally operate near their service speed with relatively low hotel (ship service) loads. For these ships, mechanical drive propulsion is often the preferred architecture. Similarly, some naval ships have relatively small ship service loads and the economical transit speed for fuel tank sizing is low enough to be able to be met with diesel engines; these ships are well suited for a mechanical drive architecture in a CODAG or CODOG configuration.

The number of shafts is usually determined by survivability requirements and by the maximum power that is practical to be delivered by a propeller. Survivability requirements for 'Compromised Mobility' speed often lead to the requirement for two shafts. If this speed is low enough, a forward drop down propulsor may be adequate to achieve these speeds. Furthermore, the amount of power per shaft should be limited to about 40 MW (50 MW maximum) based on propeller size limitations and material properties of the metals commonly used in propellers.

Ships that have a large ship service load when operating at low speed or inport, but have a smaller ship service load when operating at maximum speed may benefit from hybrid or IPS configurations. Ships that have a ship service load large enough to require medium voltage should also consider hybrid and IPS architectures; the incremental cost of adding propulsion to the electric power system is often less than adding a separate propulsion system. Integrating ship service and propulsion at endurance speeds can result in greater fuel efficiency and smaller fuel tanks. If the ship has loads (or is anticipated to have loads) rivaling propulsion requirements, then an IPS architecture is likely to be the "best" architecture.

Many cruise ships (and other types of ships) employ azimuthing thrusters (pods) in place of traditional shafts, propellers, and rudders. These azimuthing thrusters improve fuel efficiency while minimizing the need for interior volume for machinery spaces.

Ships that have acoustic requirements at low speeds should consider hybrid and IPS architectures where the electric motors are used for quiet operation. This consideration may be important to naval vessels employing sonar to detect submarines. Quiet operation may also be advantageous to cruise ships operating in environmentally sensitive areas and for research vessels.

Modern ice breakers normally employ an IPS architecture, often with azimuthing thrusters. Older ice breakers used electric drive.

IPS affords the opportunity for arrangement flexibility; this flexibility may be exploited by commercial ships to increase revenue generating capability and by naval ships in increasing mission effectiveness. Cruise ships for example, often employ IPS to maximize the number of revenue-generating staterooms. Designing a ship based on mechanical drive or hybrid considerations, then forcing an IPS to fit within these constraints is not likely to result in an optimal IPS implementation.

MARPOL emission limitations are also driving many commercial ship designs to IPS architectures; IPS enables operating prime movers at their most efficient operating point, reducing overall emissions including CO_2. To eliminate emissions, some ferries are employing IPS without any prime movers; all power is provided by energy storage that is recharged inport.

Traditional electric drive (not integrated with ship service loads as with IPS) has for the most part not been employed in ship designs since the 1980's when IPS became possible. Electric drive may prove advantageous in the future under a set of special requirements and conditions.

4. References

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McCoy, Timothy J., "Integrated Power Systems - An Outline of Requirements and Functionalities for Ships," in Proceedings of the IEEE, vol. 103, no. 12, pp. 2276-2284, Dec. 2015,

IEEE Std 45.1 IEEE Recommended Practice for Electrical Installations on Shipboard—Design

MIL-STD-1399-300-1 Low Voltage Electric Power, Alternating Current

MIL-STD-1399-300-2 Medium Voltage Electric Power, Alternating Current