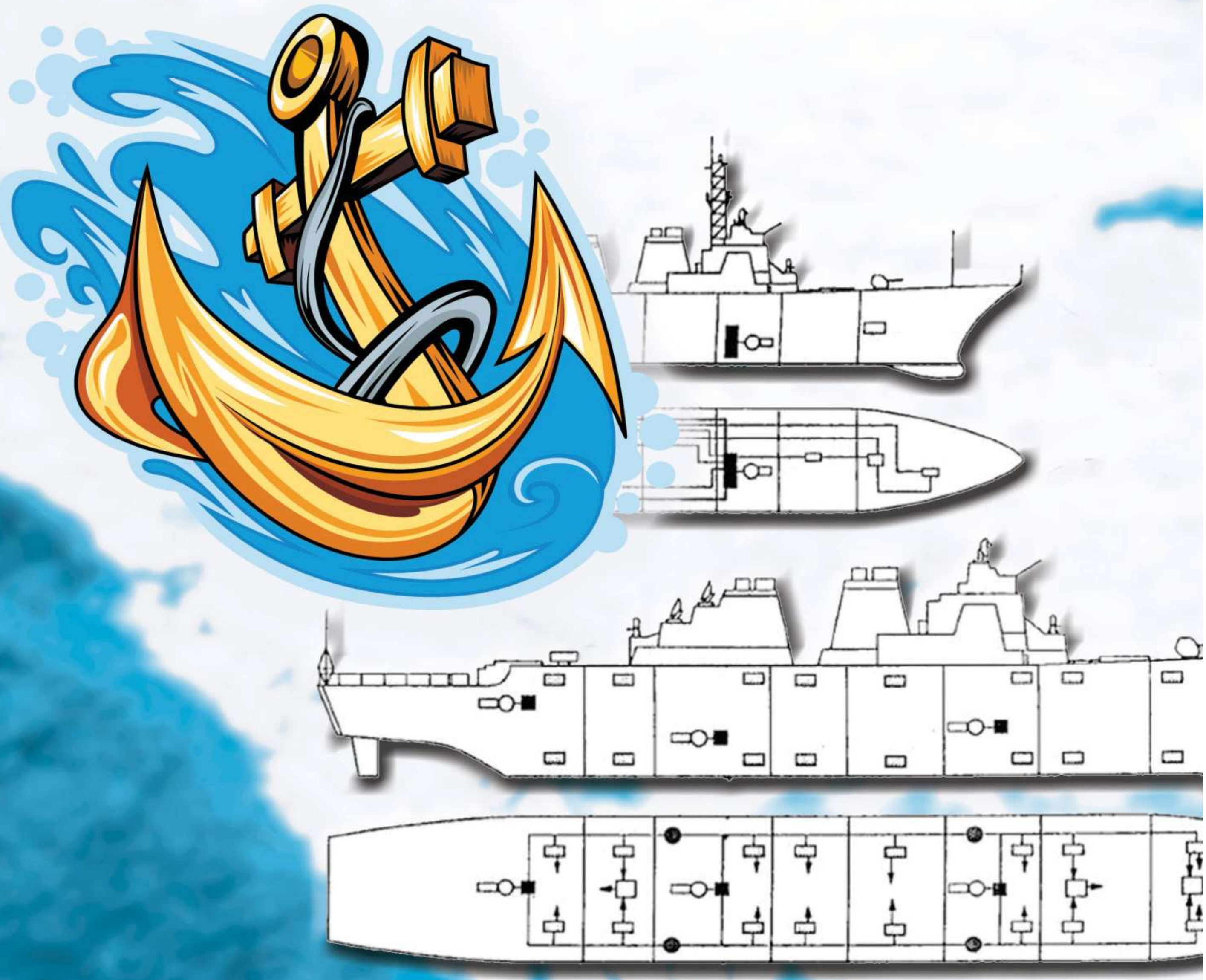
By Norbert Doerry

Naval Power Systems

Integrated power systems for the continuity of the electrical power supply.



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MIRRORING THE TERRESTRIAL POWER SYSTEM, NAVAL WARSHIPS have employed electrical power systems for over 100 years. The design philosophy for naval power systems is expressed well by the Naval Sea Systems Command (NAVSEA) *Design Practices and Criteria Manual, Electrical Systems for Surface Ships*, Chapter 300:

> The primary aim of the electric power system design will be for survivability and continuity of the electrical power supply. To insure continuity of service, consideration shall be given to the number, size and location of generators, switchboards, and to the type of electrical distribution systems to be installed and the suitability for segregating or isolating damaged sections of the system.

Naval Power System Characteristics

While much of the equipment and many of the methods and standards are common between terrestrial grid-based power systems and naval power systems, naval power system characteristics are more closely matched to islanded microgrids.

- *Variable frequency*: The frequency cannot be assumed to be constant aboard ship. The limited rotational inertia of the prime movers and generators allows for rapid accelerations and decelerations of the shaft and corresponding frequency fluctuations in response to load changes. Frequency fluctuations can be expected to last up to 2 s.
- *Lack of time-scale separation*: For naval power systems, the principal time constants of controls, machine dynamics, and electric dynamics all fall within the same general range of milliseconds to seconds. The practice of decomposing the problem by time-scale separation, which is often used in analyzing commercial power systems, becomes much more difficult.
- *Load sharing instead of power scheduling*: The commercial power utilities operate by scheduling the power delivered by each of the generating units. The mismatch between scheduled power generation and the actual load is met by the equipment acting as a swing generator. Aboard the ship, however, both real and reactive power are shared equally among all paralleled generators through the fast exchange of load-sharing information. This fast exchange of information strongly amplifies the dynamics of all the paralleled generators.
- *Short electrical distances*: The distances on board a ship are short (typically under 350 m), making the modeling of transmission lines unnecessary for many applications and trivializing the load-flow problem, which is important to the commercial power sector. The short electrical distances also strengthen the dynamic coupling of the various subsystems making up the electrical power system.
- *Load dynamics*: Commercial utilities usually assume loads are either consuming constant real and reactive power or are constant impedances. Shipboard systems, however, must account for the dynamics of loads such as propulsion motors, large pumps, pulsed loads, propeller dynamics, and ship dynamics.
- *Tighter control*: Because a ship is relatively small, a higher level of centralized control can be exercised over the shipboard power system than can be exercised in the commercial power industry.
- *Ungrounded or high-impedance grounded systems*: Naval power systems are designed to enable continued operation with a single line to ground fault.

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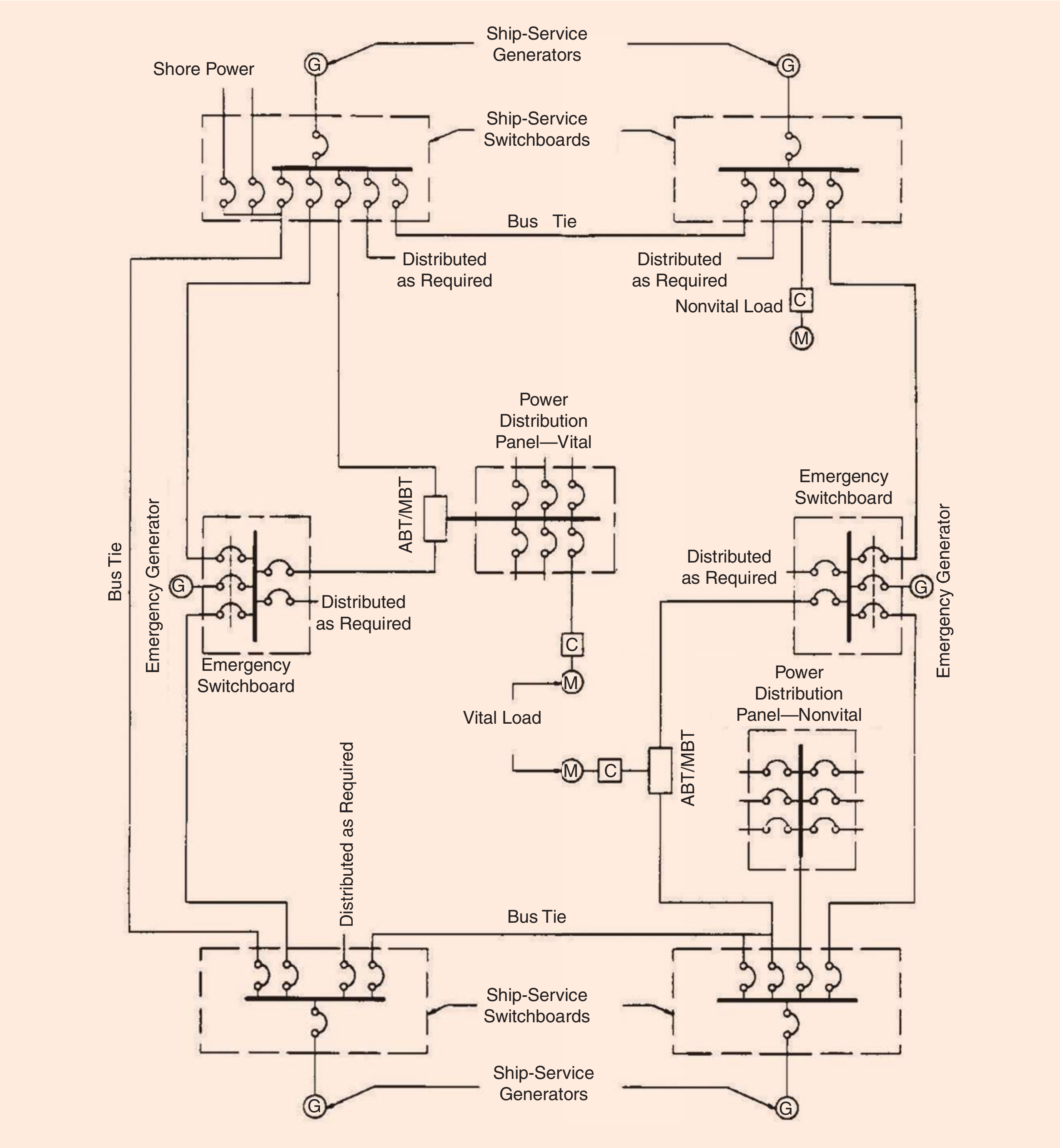

Figure 1. A radial distribution system. (Image courtesy of the U.S. Navy.) ABT: automatic bus transfer; MBT: manual bus transfer.

- *Physical environment*: Shipboard power system equipment must be able to operate in a pitching and rolling ship. Vibration, humidity, salinity, and shock must all be accounted for in the design.

Zonal Distribution

Virtually all U.S. naval ships generate and distribute three-phase 60-Hz electrical power at 440 or 4,160 V. The governing power quality interface standards are MIL-STD-1399 section 300 and section 680. Traditionally, the U.S. Navy used radial distribution systems (Figure 1) and provided vital loads with alternate sources of power from different switchboards. During the 1990s, the Navy introduced zonal distribution systems in response to the ever-increasing number of vital loads. In a radial system, vital loads are provided with alternate sources of power via longitudinal feeder cables from different switchboards. In a zonal system, vital loads are provided with alternate sources via shorter transverse feeder cables from port and starboard switchboards. By replacing long feeder cables with short feeder cables, zonal distribution systems reduce cost and weight (Figure 2).

Voltage

The choice of voltage for generation and distribution is based on cost. Generally, affordable circuit breakers are available for 440-V distribution up to 4,000 A and for 4.16 and 13.8 kV up to 3,500 A. A typical power cable can only carry 350–400 A—any larger and the bend radius would be too large to successfully arrange in a ship design. Hence, when the current requirements for a 440-V bus exceed 4,000 A, a shift to a 4.16-kV distribution system should be considered. The load that shipboard power systems must provide has experienced considerable growth with the introduction of high-power combat systems and the electrification of auxiliary equipment. The growth in electrical demand has been met on many ships by employing 4.16-kV generation and distribution with zonal transformers to provide power to the end user. For many years, 4.16 kV has been used on *Nimitz*-class [multipurpose aircraft carrier (nuclear-propulsion) (CVN) 68] aircraft carriers; it has also been used on amphibious assault ships since the *USS Makin Island* [amphibious assault ship (multipurpose) (LHD) 8] and will be included in the upcoming flight III of the *Arleigh Burke* [guided missile destroyer (DDG) 51] class of destroyers (Figure 3) as well as the *Zumwalt* (DDG 1000) class of destroyers.

> **Silicon carbide power electronics is one example of an evolving technology that has significant implications for naval power system design.**

Benefits of Integrated Power

Another ongoing trend in naval power systems is the integration of the ship's propulsion with the electrical system. For the U.S. Navy, auxiliary ships have led the way in incorporating modern integrated power systems (IPSs). In the 1980s and 1990s, ocean surveillance and oceanographic research ships employed diesel electric propulsion at relatively low power (2–5 MW per shaft). More recently, the *Lewis and Clark* (T-AKE 1; "T-" indicates the ship is operated by the Military Sealift Command while the "AKE" indicates a dry cargo and ammunition ship) class of dry cargo/ammunition ships was constructed with a 6.6-kV integrated power system with two 11-MW motors. The *USS Makin Island* (LHD 8) introduced a hybrid electric drive (HED) to the fleet (Figure 4). An HED adds a propulsion motor to the gearbox of a mechanical drive propulsion system to allow the

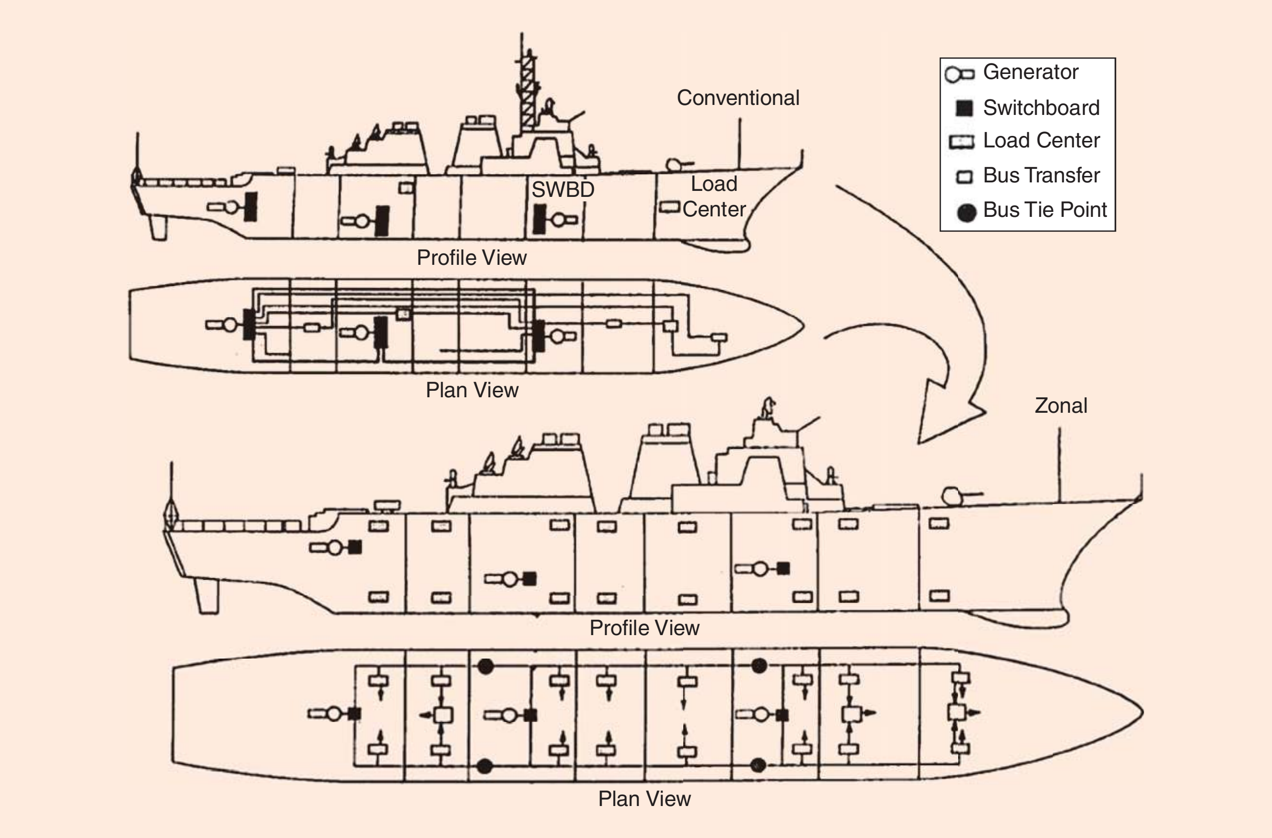

Figure 2. A comparison of radial and zonal distribution systems. (Image courtesy of the U.S. Navy.)

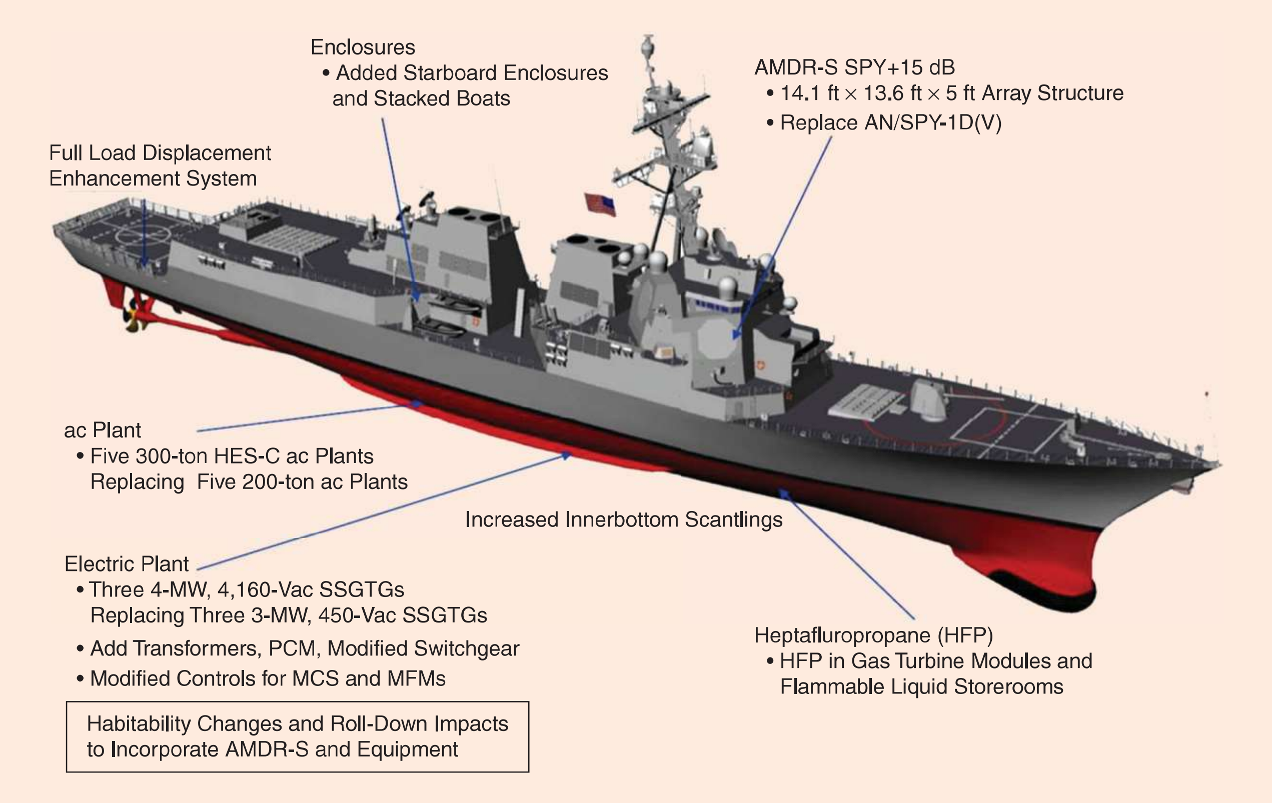

Figure 3. The layout of DDG 51 Flight III. AMDR-S: air and missile defense radar-S-band.

Figure 4. The *USS Makin Island* (LHD 8). (Photo courtesy of the U.S. Navy.)

Figure 5. The *USS Zumwalt* (DDG 1000). (Photo courtesy of the U.S. Navy.)

electrical distribution system to power the ship at low speeds. Since propulsion engines are least efficient at low power, using the electric motors can save a considerable amount of fuel when operating at a low speed. For the *USS Makin Island*, the 5,000-hp propulsion motors can operate at up to 12 kn using fuel-efficient diesel electric propulsion. Since the *USS Makin Island* is anticipated to operate at 12 kn about 70% of the time, the fuel savings are projected to be significant. HED technology is currently being built into the amphibious assault ships of the *America* [amphibious assault ship (general purpose) (LHA) 5] class and is planned for backfit into destroyers of the *Arleigh Burke* (DDG 51) class.

The *Zumwalt* (DDG 1000) class of destroyers (Figure 5) will be the first surface combatants with an IPS that supplies electrical power for both propulsion and ship-service loads. Power is generated and distributed via a 4.16-kV, three-phase, 60-Hz high-power bus. The 4.16-kV bus is used directly by the propulsion motors and to supply a 1,000-V dc lower-power ship-service bus via a transformer rectifier. Ship service loads are provided power, either ac or dc, from zonal power conversion equipment.

The reasons for using an IPS instead of having separate propulsion and electrical distribution systems are as follows:

- IPSs support high-power mission systems. Future weapons systems will continue to increase demand for electrical generation capacity. In many cases, the need for additional power will not be required at the same time as maximum propulsion power, enabling the same prime movers to be shared for propulsion and weapons systems. Examples of high-power mission systems include laser weapons (Figure 6), electromagnetic rail guns (EMRGs) (Figure 7), electromagnetic launchers, electronic warfare systems, and high-power radars.

- IPSs reduce the number of prime movers. A typical IPS configuration incorporates four to five prime movers as part of generator sets. Equivalent nonintegrated configurations employing a mechanical drive and reduction gears instead of propulsion motors would typically use four prime movers for propulsion and three to five generator sets for electrical power generation (Figure 8). The total reduction in prime movers can contribute to acquisition savings, reduced maintenance costs, reduced volume required for intakes and uptakes, and reduced manpower requirements.
- IPSs improve the efficiency of prime movers. Through the integration of ship service electrical power and propulsion power, the overall system efficiency of an IPS configuration can be considerably higher than that of an equivalent mechanical drive design, particularly at low speeds. The overall efficiency of a mechanical drive ship suffers because the propulsion prime movers are inefficient when lightly loaded. Since the required propulsion power is approximately proportional to the cube of speed and ships seldom operate at maximum speed, the required amount of propulsion power is significantly less than the maximum propulsion power a vast majority of the time. With the introduction of integrated plants, the ship service and propulsion loads are managed off the same distributed system, enabling more efficient power management.
- IPSs improve the efficiency of propulsors. The integration of an IPS in the design of a ship offers new options for propulsion system design. The propulsion-shaft line can be simplified with the removal of the traditional controllable pitch propeller (CPP) system. CPPs are currently the state of the practice for major surface combatants in world navies because they enable control of the ship's speed, both forward and reverse, when coupled with prime movers such as diesels and gas turbines that are not reversible and may have a minimum operating rotational speed. As compared to fixed pitched propellers (FPPs), CPPs have a larger hub to hold the apparatus for adjusting pitch. This larger hub reduces the efficiency of the CPP. Since a propulsion motor is fully

Figure 6. The laser weapon system. (Photo courtesy of the U.S. Navy.)

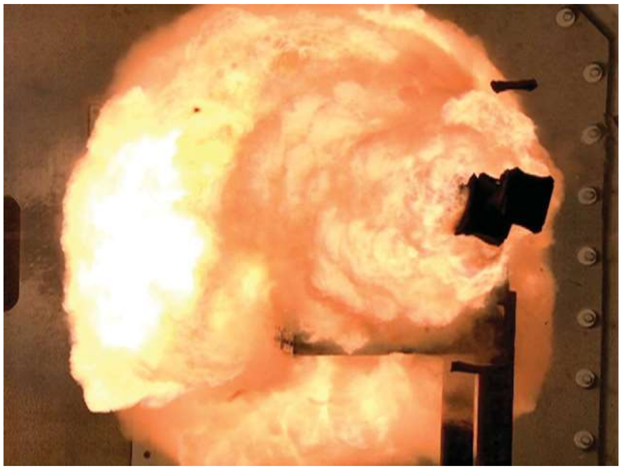

Figure 7. A test firing of an EMRG. (Photo courtesy of the U.S. Navy.)

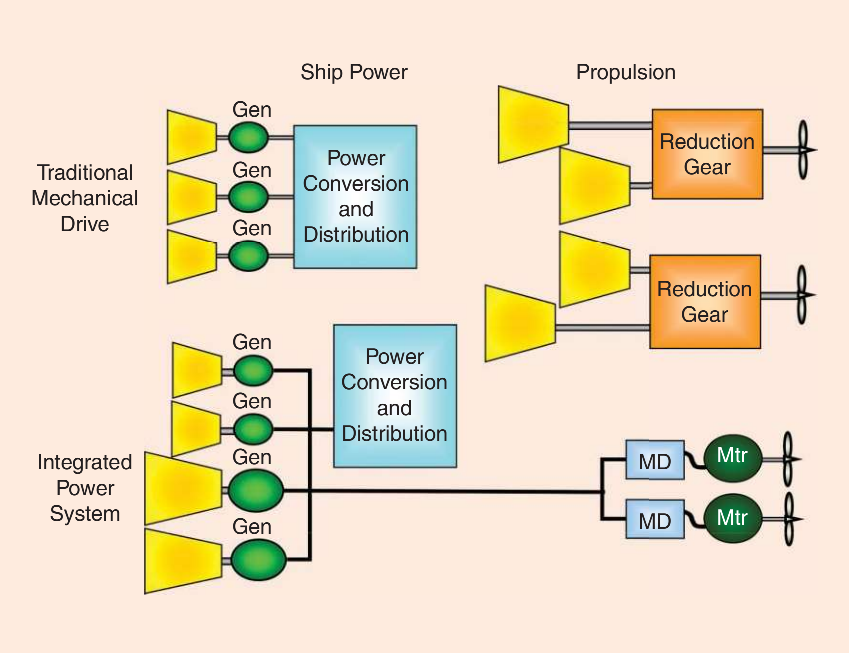

Figure 8. A comparison of traditional mechanical drive and IPSs. MD: motor drive; Mtr: motor; Gen: generator.

Figure 9. Contrarotation through a traditional propeller, shaft, and pod. (Photo courtesy of the U.S. Navy.)

reversible and can operate over the entire range from zero to maximum speed, IPSs can employ FPPs. Additionally, an IPS is well suited for incorporating pod propulsion and contra-rotating (CR) propellers. Pod propulsion is well established in the cruise line industry but has not yet been introduced in surface combatants for the U.S. Navy. CR propellers are desirable because of improved efficiency that results from the second propeller recovering wake energy from the first propeller's wake that would otherwise be lost. Since IPS configurations typically employ independent motors on the same shaft to improve reliability, dedicating each motor to its own propeller to yield improved efficiency does not add significant complexity or cost. Alternately, a traditional propulsion shaft and propeller can be paired with a pod to provide contrarotation without using inner and outer shafts (Figure 9).

- IPSs provide general arrangements flexibility. Mechanical drive ships locate the prime movers low in the ship to align with the propeller shafts. An IPS-configured ship offers the designer the flexibility to put the power generators in almost any location (after taking stability constraints into consideration). The shaft line can be simplified with direct drive motors. Future ship designers could also improve the longitudinal separation of propulsors to improve survivability without incorporating long shaft lines. The volume required for combustion air and exhaust will likely decline because of the reduced number of prime movers and can be reduced further if generator sets are located higher in the ship.

The load that shipboard power systems must provide has experienced considerable growth with the introduction of high-power combat systems and the electrification of auxiliary equipment.

- IPSs improve ship producability. For example, the elimination of long shaft lines enables the ship builder to change the build sequence to simplify the erection schedule and thereby reduce the ship's construction schedule. By locating generator sets higher in the ship, the in-yard date when these items are needed can be delayed, reducing the likelihood that the equipment will be damaged during the ship's construction. Zonal distribution systems shorten cable lengths and minimize the number of spaces a cable must penetrate.
- IPSs support zonal survivability. For a distributed system, such as the electrical power system, zonal survivability is the ability of the distributed system, when experiencing internal faults due to damage or equipment failure confined to adjacent zones, to ensure loads in undamaged zones do not experience a service interruption. Zonal survivability assures damage does not propagate outside the adjacent zones where damage is experienced. At the ship level, zonal survivability facilitates the ship to maintain or restore the ship's primary missions when experiencing battle damage. Zonal survivability enables the crew to focus restoration efforts on the damaged zones, maintain situational awareness, and take appropriate restorative actions. Zonal survivability is an inherent feature of the zonal distribution system incorporated into IPS.
- IPSs improve electric power quality of service (QOS), which is a metric being introduced into shipboard power system design to measure the reliability of electrical power provided by the power system to loads. QOS is calculated as a mean time between service interruption (MTBSI), where an interruption is defined from the perspective of the load. A service interruption is measured in terms of the maximum duration that the power quality can be outside normal limits and the load can still operate properly. An interruption in service shorter than this time duration is not used in the calculation of the MTBSI. The time used in the MTBSI calculation is usually specified by an operating cycle, design reference mission, concept of operations, or an operational architecture. QOS does not take into account survivability events such as battle damage, collisions, fires, or flooding. QOS does take into account equipment failures and normal system transients. The optimal configuration of the electric plant may differ for QOS

considerations and for survivability considerations. An important QOS consideration is the ability to preserve power to loads when a generator set trips offline while damage to the distribution system and the ability to preserve power to vital mission systems loads is of major interest in the survivability analysis. For QOS, many ships operate with their electric plant paralleled in peacetime steaming and only shift to the more survivable split-plant configurations (where the ship operates two independent islands that provide independent alternate sources of power to vital loads) under threat conditions. QOS is implemented by classifying loads as uninterruptible, short-term interruptible, and long-term interruptible. By properly selecting the number and ratings of generator sets and energy storage modules and implementing the QOS concepts in the control system, the power system can be designed with a high QOS.

> ***Naval power systems are designed to enable continued operation with a single line to ground fault.***

- IPSs facilitate fuel-cell integration. Because of their inherent efficiency, fuel cells promise to play an important role in future naval power system design. Since fuel cells produce electrical power, their integration into the IPS is natural since fuel cells are simply generator sets with special characteristics. Before fuel cells can be used, however, a number of technical and ship integration issues require resolution. These issues include the following:
    - Fuel cells cannot directly use the fuels currently available aboard ship. A fuel reformer is needed to convert diesel fuel marine to a fuel compatible with the fuel cell. A fuel reformer suitable for naval warship installation does not currently exist, although prototypes have been developed.
    - Ship integration requirements such as the quantity of gas produced and the allowable back pressure do not enable proper sizing of the intake and exhaust systems. Depending on the flow requirements, this intake air could be provided by the ship's normal ventilation system or may require dedicated intakes.
    - Fuel cells typically behave slowly dynamically. Must fuel cells be integrated with energy storage to provide better transient performance? If so, how does one size and cost the requisite energy storage?

While current naval ship designs have not taken full advantage of all the opportunities of an IPS, the continued evolution of naval warships will likely see more of these benefits realized in future designs.

Integrating Mission Systems

Integrating multiple advanced mission systems on a future destroyer under 10,000 m will require employing the following tactics to reduce the needed weight and volume of the power system:

- use controls (software implementation) to obtain required power system design performance from less hardware capacity than would be needed otherwise
- energy storage resources that can be shared by the multiple advanced mission systems (and the ships' power systems) instead of each bringing their own
- a power system, such as medium-voltage dc (MVdc), capable of providing greater energy dynamics than the classic ac power systems
- power system components that can fulfill more than one power system function simultaneously, e.g., power converters, which also limit and isolate faults obviating the need for distinct circuit breakers.

High-power mission systems, particularly those characterized as pulse loads or highly dynamic stochastic loads, may lead to the use of MVdc generation and distribution aboard future naval ships. The primary reasons for employing an MVdc system are as follows:

- The speed of the prime mover is largely decoupled from the power quality of the bus. The generator can be optimized for each type of prime mover without having to incorporate reduction gears or speed increasing gears so generators are not restricted to a given number of poles. The speed can even vary across the power operating range of the prime mover to optimize efficiency and/or responsiveness.
- Power conversion equipment can operate at high frequencies, resulting in relatively smaller transformers and other electromagnetic devices.
- Without the skin effect experienced in ac power transmission, the full cross section of a dc conductor is effective in the transmission of power. Additionally, the power factor does not apply to dc systems. Depending on the voltage selection, cable weights may decrease for a given power level.
- Power electronics can control fault currents to levels considerably lower than ac systems employing conventional circuit breakers. Lower fault currents also reduce damage during faults.
- Since there is no common frequency of vibrating equipment, the acoustic signature has a broader signature with fewer tonals that can be observed in the acoustic signature of the ship when compared to a ship operating at a constant ac frequency.
- Paralleling power sources only require voltage matching and do not require time-critical phase matching. This enables generator sets to come online faster after starting, thereby reducing the aggregate amount of energy storage needed to enable operating with a single generator set online.

- Gas turbine engines with a high-speed power turbine mated with high-speed generators that produce more than 60-Hz frequency power are easily accommodated. A combination of high-speed power turbines and generators enables a shorter generator set. Shorter generator sets enable shorter machinery space lengths, which assist ship designs in meeting floodable length requirements for damaged stability. Enabling the integration of higher speed gas turbines into power systems also provides additional opportunities for competition and potential cost savings. Note that the impact of skin effect on conductor size can be mitigated with minimizing the distance between the generator and rectifier.
- High-power, highly dynamic, demanding electric mission loads (such as EMRGs, lasers, high-power radars, and electronic warfare systems) are more easily accommodated with MVdc. Because the speed of the prime mover does not directly affect power quality at the MVdc bus (as is the case with ac systems), the rotational inertia of the generator and power turbine (for multispool gas turbines) can be employed as energy storage, minimizing total ship impact of additional energy storage.

An HED adds a propulsion motor to the gearbox of a mechanical drive propulsion system to allow the electrical distribution system to power the ship at low speeds.

Before MVdc can be employed on a naval warship, a number of technical issues require resolution.

- Bus regulation and prime mover regulation: In classic ac power systems, real power is regulated through prime mover governor control of speed (frequency regulation). Reactive power is regulated through the generators' voltage regulation. DC power systems only regulate voltage. By supplying an MVdc bus with no frequency regulation requirement, the power control of the prime mover, gas turbine or diesel, is provided with an additional degree of freedom, which can be used to increase dynamic response. Other prime mover developments under consideration could provide additional improvements to the dynamic response of the prime mover itself. A number of approaches to regulating the MVdc bus are available and must be decided upon for standardization. One simple approach would be to employ a droop response wherein the bus voltage would reflect its per-unit load. An integrated dynamic would have the prime mover source respond to longer time-scale, average, load changes and the fast energy storage response to rapid pulse load changes. Criteria for assessing the different approaches for regulating the MVdc bus are necessary before selecting one. A droop response may be an appropriate reversionary mode when control communications are not present to provide commanded regulation set points.
- System grounding: While grounding considerations in an MVdc system are analogous to those in ac systems, the location of the system ground point is different. In an ac system, grounding (high impedance or otherwise) associated with the neutral point of the generator, or related point, is a logical choice. A corresponding approach for an MVdc system would be to install a resistive midpoint between the two poles. The midpoint could then be grounded (high impedance or otherwise). Other alternatives with respect to the ground point should also be considered. Distributed system capacitance is understood and specified for ac systems, however, the effect of distributed system capacitance on MVdc power systems is less studied. Guidance for specifying maximum components and system capacitance within an MVdc system is still an open research area.
- Fault detection, localization, and isolation: In ac systems, time and fault current magnitude are employed by circuit breakers to detect, localize, and isolate faults as part of an overall circuit protection system. In an MVdc system, all sources connect to the distribution bus through power electronics that can limit fault currents. Furthermore, because dc circuit breakers cannot take advantage of the zero crossing of an ac waveform to extinguish an arc, the ability of dc circuit breakers to interrupt large fault currents is limited. Using the inherent capability of power electronics to limit fault currents and new methods for fault detection, localization, and isolation is an obvious choice for MVdc. The details of how to accomplish this requires additional investigation. Reliable methods of fault detection, localization, and isolation must be developed.
- Magnetic signature: A dc current creates a constant magnetic field that can leave a residual magnetic field in ferrous materials. This residual magnetic field contributes to the overall ship magnetic signature and is susceptible to mines and magnetic influence sensors. The creation of residual magnetic fields can be minimized by physically locating conductors that are close to one another carrying currents in opposite directions so the magnetic field from one conductor can cancel out the field from the other. Ideally, a coaxial power cable would completely eliminate the magnetic field. One concern will be in the design of terminations and the routing of conductors within the power system and load equipment. Creepage and clearance requirements to prevent arc faults will require separation of conductors and locally result in

increased magnetic fields. The signature of these fields may be mitigated through magnetic shielding with the possibility of increased weight and cost. The potential for these residual magnetic fields should be considered in the design of the ship's degaussing system. As an alternative (or in addition) to magnetic shielding, developing and implementing a method for deperming these localized residual magnetic fields should be investigated.

A number of evolving technologies are enabling continuous improvements in the affordability and performance of naval power systems. The Office of Naval Research funds a spectrum of programs that will eventually transition to naval ships. The Electric Ships Office [program management office (PMS) 320] of the Naval Sea Systems Command funds the development of power systems components for integration into naval ships. Additionally, the Electric Ship Research and Development Consortium, made up of of U.S. research universities conducting naval power system research, has contributed significantly to the body of knowledge, enabling further development of MVdc systems.

> **Contrarotating propellers are desirable because of improved efficiency that results from the second propeller recovering wake energy from the first propeller's wake that would otherwise be lost.**

Silicon carbide power electronics is one example of an evolving technology that has significant implications for naval power system design. The development of commercially available, affordable silicon carbide power-electronic switching modules greatly enhances the ability of power systems to meet the challenging dynamic performance requirements and weight and size constraints. The qualities of silicon carbide modules most valuable to this effort are

- high switching speeds, which increase internal frequencies of converters (from tens of hertz to tens of kilohertz), thereby greatly reducing the size and weight of magnetic and capacitive components
- lower losses (higher converter efficiencies), which reduce thermal footprints
- higher voltage capability, which reduces switching modules required in series for MVdc applications.

The IEEE is contributing to the advancement of naval power systems through standards working groups. In particular, the IEEE 45 series of standards (*Recommended Practice for Electrical Installations on Shipboard*) is currently being updated to reflect the advances in shipboard power systems. Other IEEE standards applicable to naval power systems include

- IEEE 1662-2008, *IEEE Guide for the Design and Application of Power Electronics in Electrical Power Systems*
- IEEE 1709-2010, *IEEE Recommended Practice for 1 to 35 kV Medium Voltage DC Power Systems on Ships*
- IEEE 1826-2012, *IEEE Standard for Power Electronics Open System Interfaces in Zonal Electrical Distribution Systems Rated Above 100 kW.*

Conclusion

In summary, naval power systems are undergoing rapid evolution as the demand for onboard electrical power continues to grow. This growth is being compounded by the increased introduction of pulse loads and nonlinear stochastic loads. Increasingly, IPSs are proving to be the most economical way of powering these loads. Currently, the state of the practice includes generating and distributing power at 4.16 kV (or higher) and using zonal transformers to provide 440 V of ac power to loads. *Zumwalt* (DDG 1000) is an evolutionary advancement that employs a 1,000 V dc bus and zonal power conversion for loads. In the future, to achieve the power density and affordability constraints that will be needed for warships, MVdc will likely be employed for power generation and distribution. There is much work to be done, however, to translate MVdc technology from laboratory demonstrations to fielded products.

For Further Reading

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Biography

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