Shipboard Electrical Power System Characteristics

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1. Introduction

With the exception of uncrewed ships, shipboard electrical power systems enable ships to provide services and a suitable environment for crew and passengers, power some or all of the ship's steering, maneuvering and propulsion systems, and power equipment necessary for the ship to accomplish its missions. In ships employing an integrated power system (IPS), the same electrical power system is used for all ship service loads (also known as "hotel loads") as well as for propulsion motors. In mechanical drive ships, propulsion is provided by dedicated prime movers, typically medium-speed diesel engines or gas turbines. The electrical power system provides power to the ship service loads including electrically powered propulsion auxiliaries.

IEEE Std 45.1™ provides the following categories of electrical power system loads typically found onboard commercial ships:

100 Propulsion
200 Batteries and battery chargers
300 Power conversion equipment
400 Lighting
500 Electronics
600 Navigation systems
700 Auxiliaries
800 Heating ventilation and air conditioning systems
900 Deck machinery
1000 Food services
1100 Workshops/Laundry equipment

MIL-STD-881 identifies seven high level categories of ship systems (most requiring electrical power). These high-level categories are further broken down into smaller groups as part of the Extended Ship Work Breakdown System (ESWBS). These high-level categories, often referred to as 1-digit groups, are:

100 Hull structure
200 Propulsion plant
300 Electric plant
400 Command, communications, and surveillance
500 Auxiliary systems

600 Outfit and furnishings
700 Armament

2. Characteristics

While shipboard power systems adhere to the same laws of physics as any other power system, their unique environment results in characteristics that differ from the usual terrestrial power system and are similar to those of islanded micro-grids. Doerry (2015) lists the following characteristics of naval power systems (power systems found on warships); these characteristics are generally consistent with those of commercial ships as well:

> "• Variable frequency: The frequency cannot be assumed constant onboard 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.
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> • 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 often used in analyzing commercial power systems becomes much more difficult.
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> • 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 equipment acting as a swing generator. Onboard ship however, both real and reactive power are shared equally among all paralleled generators through the very fast exchange of load sharing information. This fast exchange of information strongly couples the dynamics of all the paralleled generators.
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> • Short electrical distances: The distances onboard ship are so short (typically under 350 m) as to make the modelling of transmission lines unnecessary for many applications and to trivialize the load flow problem which is so 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.
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> • 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 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.
- 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."

3. Power Reliability and Quality of Service

The term "reliability" implies that a system performs consistently well. In terms of maintenance planning, the metric "Mean Time Between Failure" or MTBF is used to describe how often failures occur in equipment. The criticality of equipment and the estimated MTBF are used to determine how many of what type of spare parts are kept onboard, as well as influencing the type of training the ship's crew receives.

For Quality of Service (QoS), the metric "Mean Time Between Service-Interruption" or MTBSI is used. A service interruption is usually defined in terms of the length of time that power quality is outside of prescribed standards (or power is lost altogether) as compared to the amount of time a load can tolerate the power quality being outside of prescribed standards; a service interruption only occurs if the power quality is outside of prescribed standards for a longer period of time than the load can tolerate.

To prevent service interruptions, categorizing loads with respect to two system metrics, t1 and t2 is useful. As defined in IEEE 45.1:

> "Reconfiguration time (t1) is defined as the maximum time to reconfigure the distribution system without bringing on additional generation capacity."
>
> "Generator start time (t2) is defined as the maximum time to bring the slowest power generation module online."

If a load would experience a service interruption with power outside of power quality requirements of duration t1, it is classified as an uninterruptible load.

If a load would not experience a service interruption with power outside of power quality requirements of duration t1, but would with duration t2, it is classified as a short-term interrupt load.

If a load would not experience a service interruption with power outside of power quality requirements of duration t2, it is classified as a long-term interrupt load.

Technology choices in the design of the power system impact the values of t1 and t2. The values of t1 and t2 in turn impact how loads are categorized and how the power system should be designed to minimize service interruptions.

For example, if conventional electro-mechanical circuit breakers are used in a system, then t1 can be on the order of seconds. If solid state circuit breakers are used, then t1 can be on the order of milliseconds. Many loads that would be classified as uninterruptible loads with electro-mechanical circuit breakers would be classified as short term interrupt loads with the solid state circuit breakers. Uninterruptible loads typically require distributed uninterruptible power supplies (UPS) to avoid service interruptions. With the use of solid state circuit breakers, these distributed UPSs may not be required at all, or replaced with more economical centralized UPSs.

4. Survivability

Survivability refers to the susceptibility, vulnerability, and recoverability of the power system when exposed to potential threats such as collision, flooding, fire, weapon detonation, and cyber attack. Susceptibility is the likelihood that the power system will be exposed to a potential threat. Vulnerability addresses how well the electrical system maintains power quality and power continuity following exposure to a threat. Recoverability addresses how quickly electrical power can be restored following an outage caused by a threat.

While survivability clearly applies to naval power systems; survivability also applies to commercial vessels. Like naval power systems, commercial marine power systems should be designed to be survivable when exposed to collision, flooding, fire, and cyber attack. The ability to be survivable when exposed to weapons detonation differentiates the naval power system from the commercial marine power system.

Survivability requirements for commercial ships are found in regulations (laws), international treaties, and classification society rules. The classification societies, such as the American Bureau of Shipping (ABS), Det Norske Veritas (DNV), and Lloyd's Register (LR), play an important role in commercial ship survivability; commercial ships must continuously demonstrate that they adhere to their applicable classification society in order to obtain insurance. Survivability requirements in laws and international treaties are often the result of major maritime disasters such as the loss of the RMS *Titanic* in 1912, SS *Vestris* in 1928, SS *Morro Castle* in 1930, and MS *Estonia* in 1994.

To facilitate survivability of complex ships, IEEE Std 45.3 provides guidance for zonal design. In zonal design, the ship is divided into multiple zones where the zone boundaries align with the hull and transverse watertight subdivision bulkheads. Generally, a ship employing zonal design will have between four and seven zones. In zonal design, critical mission equipment is allocated to the different zones. If possible, all non-redundant equipment supporting a critical mission should be allocated to a single zone; all redundant equipment supporting a critical mission should have at least one complete zone between them.

In zonal design, distributed systems, such as the electrical power system, are designed to provide zonal survivability. In zonal survivability, damage to one or two adjacent loads does not result in service interruptions in undamaged zones. This impacts both the selection of electrical distribution system architecture, and the choice and location of electrical power sources.

Additionally, compartment survivability is provided to critical loads in damaged zones. In compartment survivability, provisions are made to quickly recover electrical power to critical loads that are undamaged and for which energizing the equipment can be performed safely.

In naval power systems, casualty power systems may be employed to address recoverability after damage to the power system. Casualty power systems are composed of a series of portable cables, permanently installed cables, connectors, and bulkhead penetrations designed to enable restoring power to undamaged equipment within a damaged zone or compartment.

5. Marine Environment

Shipboard power systems operate in a challenging environment. Ships roll, pitch, slam and may have steady-state lists or trims; level operation is rarely achieved. The atmosphere may have extreme temperature variations, high salt content, and high humidity. Equipment may be subject to high levels of vibration and in the case of naval power systems, be subject to shock and blast from weapons effects. Other possible conditions include exposure to damaging fumes or vapors, abrasive particles, salt-spray, ice, and sunlight. For these reasons, industrial equipment must often be modified to work satisfactorily in a marine environment.

IEEE Std 45.1 provides guidance for shipboard environmental conditions to use in the design of shipboard power systems. For naval systems, MIL-DTL-917, MIL-DTL-901, MIL-STD-167-1, MIL-STD-1399-301, and MIL-STD-1399-302 should be consulted.

6. References

Doerry, Norbert, "Naval Power Systems," IEEE Electrification, Volume 3 Number 2, June 2015, pp. 12-21.

IEEE Std 45.1, IEEE Recommended Practice for Electrical Installations on Shipboard – Design

IEEE Std 45.3, IEEE Recommend Practice for Shipboard Electrical Installations – Systems Engineering

MIL-DTL-901, Shock Tests, H.I. (High-Impact) Shipboard Machinery, Equipment, and Systems, Requirements for

MIL-DTL-917, Electric Power Equipment, Basic Requirements for

MIL-STD-167-1, Mechanical Vibrations of Shipboard Equipment (Type I – Environmental and Type II – Internally Excited)

MIL-STD-881, Work Breakdown Structures for Defense Materiel Items

MIL-STD-1399-301, Department of Defense Interface Standard - Interface Standard for Shipboard Systems Section 301A Ship Motion and Attitude

MIL-STD-1399-302 Department of Defense Interface Standard - Interface Standard for Shipboard Systems Section 302 Weather Environment