Shipboard Power Systems vs Terrestrial Power Systems

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1. Introduction

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 and industrial applications. 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."

This document discusses most of these characteristics under the following four topics:

a. Power Management and System Control

b. Fault Management

c. Cable Lengths

d. Load Management

2. Power Management and System Control

In terrestrial power systems, the interconnected grid has a considerable amount of inertia; most loads are small enough in comparison to the total electrical load such that sudden additions or removals of electrical load do not impact system voltages or frequencies. Most generators operate at or near their most efficient operating point; they typically operate near their rated power capacity. The amount of power produced by most generators is scheduled ahead of time based on predictions of the load. The grid operators closely monitor bus frequency and voltage. If the system frequency begins to drop below nominal (60 Hz. In the United States), then the total load is greater than generation. To restore the frequency back to nominal, specific generators are commanded to increase the amount of power they produce in order to restore balance (and system frequency). Similarly, if the system frequency rises above nominal, the load is less than generation, and specific generators are commanded to decrease the amount of power they produce. Some generator technologies require seconds to respond to change in load commands; others generators, such as those powered by gas turbines, can respond in less than a second. Many energy storage technologies can respond to load commands in milliseconds.

In the terrestrial power system, voltage set points for generators are established to keep the nominal system voltage within tolerance everywhere in the grid while keeping reactive power provided by the generators within bounds. These set points are established based on performing a load flow analysis; the impedances of the long cables interconnecting generators and loads are a major factor in determining the load flow solution. The grid operators also have the ability to adjust the output voltage of some transformers with tap changers. Voltage regulation depends on managing the flow of reactive power (measured in VARs). Capacitors, static VAR compensators, and synchronous condensers are tools the grid operator can use to produce or consume VARs as needed.

In shipboard power systems, it is possible that individual loads can have a magnitude that is a significant fraction of the amount of power being produced at any one time. These loads typically include electric propulsion, maneuvering thrusters, large pumps, large ventilation fans, and for naval ships, weapons systems. When these loads turn on or off, or change their operating mode, the power system may see large transients in their frequency and voltage waveforms that can last for up to 2 seconds. Older ships may still employ droop for sharing the load among paralleled generator sets. With droop, the amount of real power provided by a generator is a function of the system frequency, and the amount of reactive power provided is a function of voltage; the steady-state system voltage and frequency are rarely at their nominal values. Newer ships exchange control signals among paralleled generators to implement real and reactive power sharing while regulating the system frequency and voltage to their nominal values.

In deciding which generators are on, and how much power each generator is commanded to produce, the terrestrial grid operators seek to minimize cost while assuring a level of system resiliency to contingencies. The grid operators relay on sophisticated computer optimization algorithms to make their decisions.

Because shipboard systems have only a few (typically 2 to 6) generator sets, and these generator sets are usually of only 1 or 2 models, the optimal line-ups and sharing strategies can usually be determined as part of the design process. The operator in many cases is trained to know and implement the optimal line-up for different ship operational conditions. In some newer ships, the process of deciding which of the predefined line-ups to use is completely automated.

The time required to bring a new generator online is typically longer for terrestrial power systems. The fastest generator sets, simple cycle gas turbine generators used for peaking applications, can be online at full load in as little as five minutes. Most of the power generated in the United States is produced by power plants that require more than 1 hour from cold shut down to full load (see https://www.eia.gov/todayinenergy/detail.php?id=45956). For shipboard systems, generator sets are typically online and loaded from as fast as 10 seconds up to 2 minutes. Some larger generator sets used in ships with electric propulsion may take slightly longer than 2 minutes. Consequently, shipboard engineers can react much faster to required changes in plant line-up than their terrestrial grid operator counterparts.

3. Fault Management

Terrestrial power systems are typically solidly grounded; both line to line faults and line to ground faults result in large fault currents that trip protection devices such as circuit breakers.

Since many faults are self-clearing (the cause of the fault is either vaporized or otherwise removed), terrestrial power systems will often automatically attempt to reclose tripped circuit breakers after a few seconds. Several attempts at reclosing the circuit breaker may be performed before the system concludes that the fault is not temporary and leaves the circuit breaker tripped. Fault currents are generally limited by the impedances of the long cables between the generators and the fault.

Shipboard power systems are mostly ungrounded or high-resistance (HRG) grounded. In these systems, continuous operation is possible with the first line to ground fault. Continuous operation of critical systems ensures the safety of the ship in restricted maneuverability and other potentially hazardous conditions. In this aspect, shipboard power systems are more similar to terrestrial industrial power systems than to terrestrial electrical transmission and distribution systems.

In shipboard power systems, the impedances of the short cables between the generator and the fault can result in high fault currents; attention must be given to ensuring circuit breakers and other distribution system equipment are capable of interrupting the fault current available from the online generator sets. Available fault current and interruption capability of circuit breakers is a significant driver for determining the nominal system voltage of the main power generation bus onboard ship. Available fault current and interruption capability can also limit the power rating of medium voltage to low voltage transformers.

4. Cable Length

In addition to the impact on fault currents as described in the previous section, the lower impedances of short cables between paralleled generators more tightly couples their dynamic response to disturbances. A considerable amount of attention must be paid to system stability in shipboard systems, especially when generator sets of different types are paralleled. If two shipboard generators of very different rated powers are paralleled, it may be possible that their dynamic response may result in the smaller rated generator tripping off line, followed by overloading of the larger generator, followed by the larger generator tripping off line, and resulting in a complete power outage. A robust dynamic analysis effort should be performed to ensure the shipboard power system will operate as intended within the shipboard operational environment.

In terrestrial power systems, stability analysis is usually simpler in that generator sets are assumed to parallel with an infinite grid through the relatively large impedances of longer cables. Simplifying assumptions can be made within this environment that are not appropriate for shipboard systems.

5. Load Management

Both terrestrial power systems and shipboard power systems are designed to serve all loads under normal conditions. However, terrestrial power systems usually have more rolling reserve (online generator capacity minus the current operating load) than shipboard power systems; the loss of any one online generator typically does not impact the ability of terrestrial power systems to serve all loads. Shipboard power systems typically do not operate with sufficient online generator capacity to serve all loads upon loss of a single online generator. Shipboard power systems usually rely upon load management in the form of load shedding to reduce the load when needed so that online generator capacity is greater than the remaining load. Power to these loads is restored once additional generator capacity is brought online.

In shipboard power systems, certain large loads must communicate with the control system to ensure adequate capacity is available to serve the load, before the load is allowed to draw significant power. Examples of such loads include electric propulsion and large ventilation fans.

6. Concluding Thoughts

While shipboard power systems are different in several key ways, it is important to remember that much of the electrical distribution equipment and components are similar or the same as for terrestrial systems. Hence many of the design tools, analytic procedures, and practices are the similar or the same. However, some key analytic procedures and practices must deviate from those used for terrestrial systems due to the unique circumstances associated with shipboard power systems. One should understand these deviations when selecting design and analysis tools; the assumptions behind these tools may be wholly appropriate for terrestrial systems and wholly inappropriate for shipboard systems. Engineer beware!

7. References

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