Architectures

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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. Other architectures are possible, but are not commonly found. The elements of an electrical power system as defined by Doerry and Davis (1994) and Doerry et al. (1996) are:

- Power Generation
- Power Distribution
- Power Conversion
- Energy Storage
- Platform Load
- Propulsion Power (or Propulsion Motor)
- Power Management (or Power Control)

These elements are implemented in the hardware and software of a corresponding module. The interconnections between the modules are in the form of power cable connections, and control system signals.

The power system architecture is influenced by design decisions including whether power generation is done at low voltage (below 1 kV) or at medium voltage (between 1 kV and 18 kV) and whether the power generation is AC or DC.

Shipboard propulsion architectures are usually classified as mechanical drive (MD), hybrid electric drive (HED), integrated power systems (IPS), and electric drive (ED).

2. Electrical Power System Architectural Modules

2.1. Power Generation Modules (PGM)

A PGM converts fuel or any other source of energy into electrical power for use onboard the ship. Power flow (other than for control and auxiliaries) is intended to be unidirectional from the PGM to a PDM. Common PGMs are diesel generator sets and gas turbine generator sets. Fuel cells, waste heat recovery systems that produce electrical power, and photovoltaic systems are other PGMs that may be integrated into a shipboard power system.

2.2. Power Distribution Modules (PDM)

Power distribution provides electrical power connectivity between other modules. A PDM is composed of components such as electrical power cable (both feeder cables and bus ties between switchboards), switchboards, load centers, power panels, fault protection relays, automatic paralleling devices, and bus transfer devices. PDMs may include harmonic filters and other devices to maintain power quality.

2.3. Power Conversion Modules (PCM)

A PCM converts electrical power from one type to electrical power of another type. A power type can be AC or DC, voltage, number of phases, separately derived system (ground reference), or a specified power quality. Transformers are PCMs that are often used to convert AC power of one voltage to AC power of another voltage. Power electronic converters, inverters, and rectifiers are more generalized PCMs.

2.4. Energy Storage Module (ESM)

Energy storage is used to store electrical energy. An ESM may have one or more bi-directional electrical power interface, or may have dedicated unidirectional power interfaces for charging and discharging. When acting as a load, it stores energy from the PDM; when acting as a source, it provides energy to the PDM. ESMs may be implemented with technologies such as batteries, flywheels, ultra-capacitors, and super-conducting magnetic energy storage. An ESM may include power electronics to convert the stored energy to the form needed by the power system interface. An ESM may also include control hardware and software. An ESM is characterized by the amount of energy it can store (kW-h), the rated charging power (kW) and the rated discharging power (kW).

2.5. Platform Load Module (PLM)

The platform loads (or simply "loads") are all of the loads as listed in the ship's Electric Power Load Analysis (EPLA) with the exception of equipment comprising a PMM. Under normal conditions, power is unidirectional from the PDM into a platform load. Under transient conditions, the loads may provide some energy back into the PDM.

2.6. Propulsion Motor Module (PMM)

A propulsion motor module converts electrical power from a PDM into mechanical power for the purpose of propelling the ship. A PMM typically consists of a motor drive, propulsion motor, dynamic braking resistor, associated controls, and possibly a propulsion transformer. One type of PMM, the electrically powered azimuthing thruster (pod), includes the propulsor and possibly a steering mechanism.

When the ship is dynamic braking, the PMM can either dissipate the regenerative power in a dynamic braking resistor, or provide power back to the PDM. Using a dynamic braking resistor is simpler to implement, but does require a method for dissipating the heat generated from the dynamic braking resistor.

In hybrid-electric drives where the propulsion motor is integrated with a prime mover, it may be possible to employ the PMM as a PGM and supply power to the PDM.

2.7. Power Control Module (PCON)

Control systems are comprised of the software, and possibly the hardware, needed to successfully operate and maintain the electrical power system.

3. Electrical System Architectures

3.1. Radial architecture

In a radial architecture, every switchboard (PDM) has a source (PGM, PCM or ESM) connected to it. All loads are powered via a single switchboard (PDM) at any given time, possibly via intermediary load centers (PDM) and power panels (PDM). Power flow from the switchboard to the load (PLM) is unidirectional. Switchboards are inter-connected with bus-ties (PDM) to enable powering one switchboard from the source on another switchboard. Critical loads have a bus transfer (PDM) that enables switching its supply connection from one switchboard to another. These bus transfers can be manually operated (MBT), automatically operated (ABT), or implemented with power electronics (SSABT). The bus transfer may be located at the load, at the input to a power panel, or at the input of a load center.

Loads connected to each switchboard may be located anywhere onboard the ship.

If all the switchboards are configured such that they are all electrically connected, then the electrical power system is said to be connected for parallel plant operation. If the switchboards are configured such that the electrical power system is operated as two or more independent systems, the electrical power system is said to be connected for split plant operation.

Figure 1 depicts an example of a low voltage radial distribution system. Figure 2 depicts a radial architecture for a system with medium voltage power generation. Although not depicted, some loads may be directly connected to switchboards. Also note that for clarity, cables are depicted as solid lines; cables are actually part of a PDM.

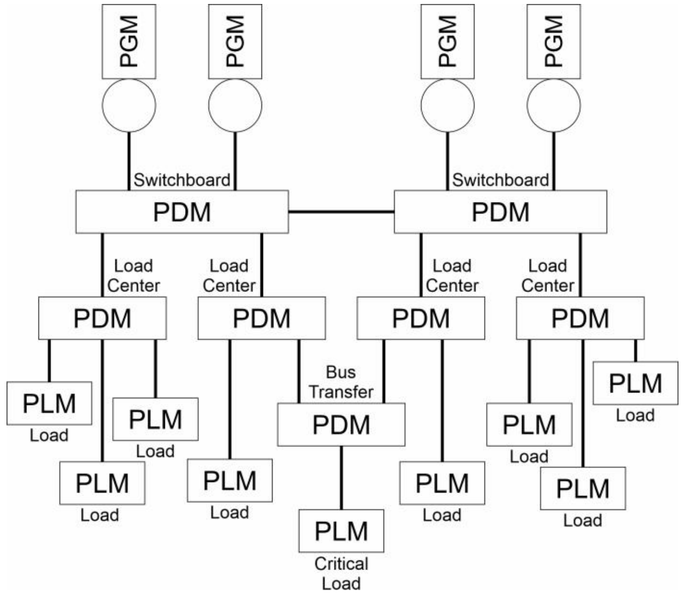


Figure 1 Example of a Low Voltage Radial Architecture

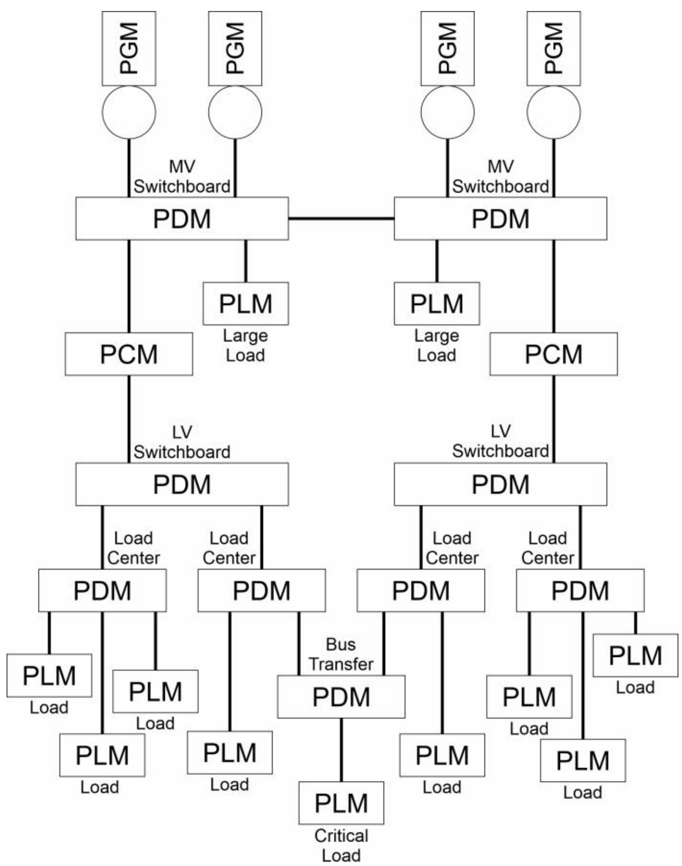


Figure 2 Example of a Medium Voltage Radial Architecture

3.2. Ring bus architecture

A ring bus architecture is similar to a radial architecture with the following exceptions:

a. Not every switchboard need have an associated source.
b. The switchboards are connected in a ring such that power connectivity is maintained with all switchboards with the loss of an arbitrary bus-tie.

A ring bus architecture is normally operated for parallel plant operation with all bus-ties closed. The selective opening of bus-ties does enable split-plant operation; the ring bus architecture enables a quick recovery of power to a switchboard due to loss of an arbitrary bus-tie.

Figure 3 depicts an example of a low voltage ring bus architecture. Note that one switchboard does not have a source associated with it. Figure 4 depicts a medium voltage ring bus architecture. The bus ties between the LV switchboards would normally be open (disconnected); the bus ties are used if the PCM between an MV and LV switchboard is out of service. This example also employs bus transfer devices at the load center level instead of at the critical load level as shown in previous architecture examples.

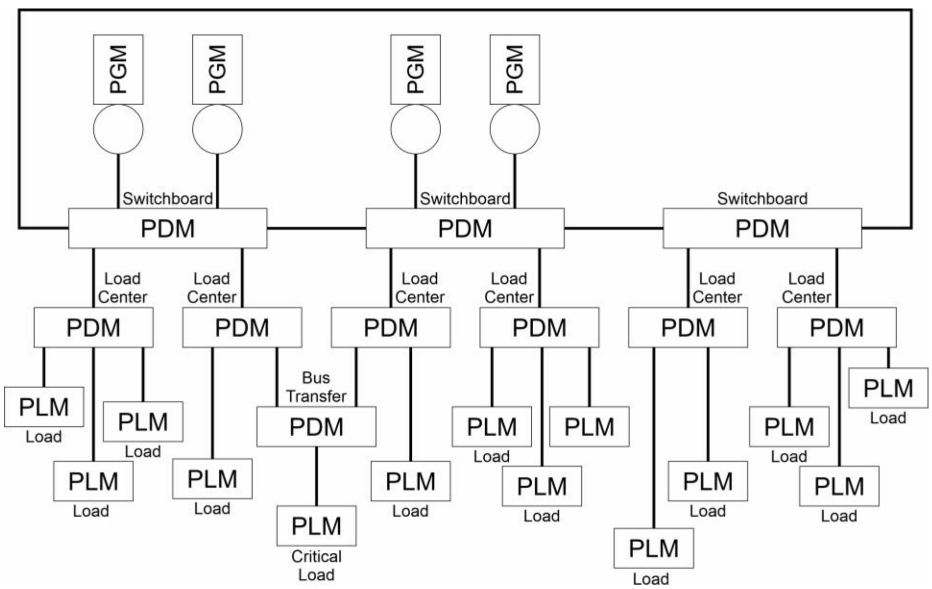


Figure 3 Example of a Low Voltage Ring Bus Architecture

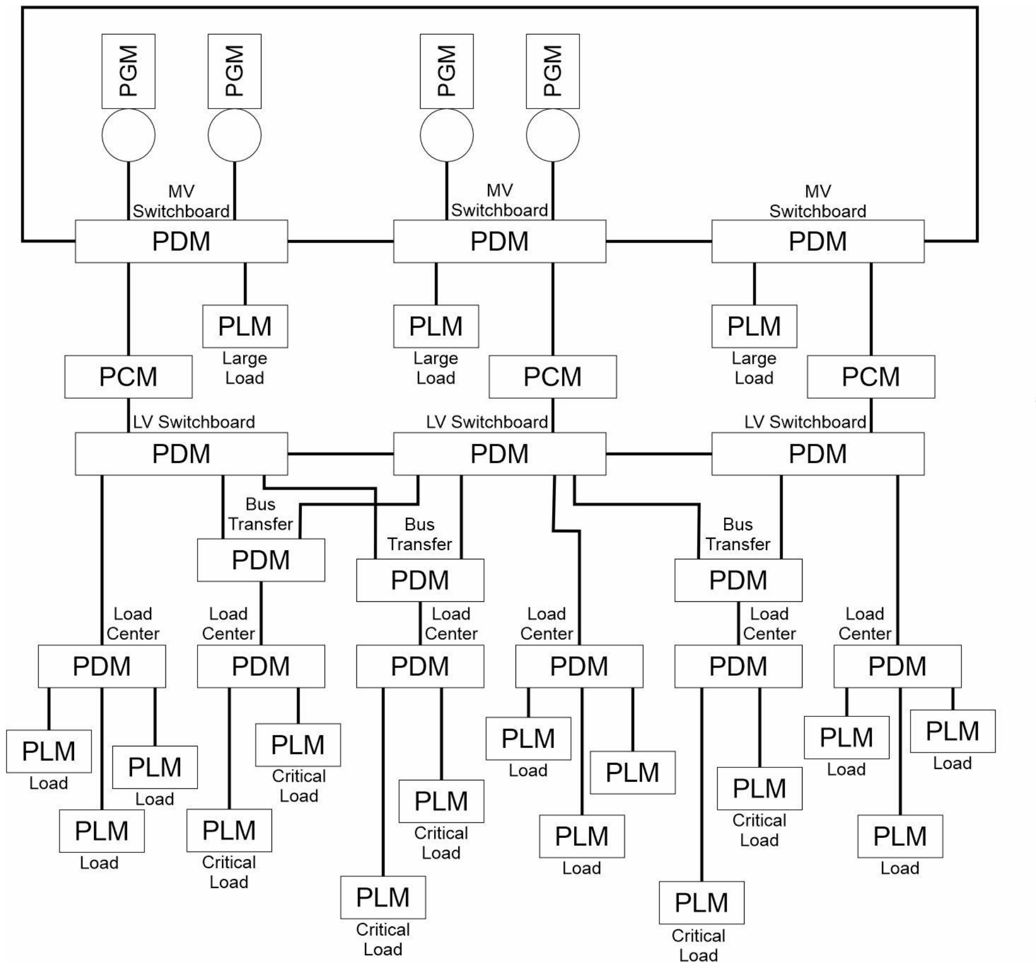


Figure 4 Example of a Medium Voltage Ring Bus Architecture

3.3. Zonal architecture

A zonal architecture is similar to a ring bus architecture with the following exceptions:

a. The ship is divided geographically into multiple zones.
b. The ring bus is usually configured as a port and starboard bus. Each bus is segmented by switchboards that provide power to load centers, possibly via a PCM. A zone is not required to have a switchboard; a load center may be powered by switchboard in another zone.
c. In ships with medium voltage generation, the ring bus is operated at medium voltage. A medium to low voltage transformer or power electronic converter (PCM) is connected to a medium voltage switchboard that is part of the ring bus, and a dedicated low voltage switchboard that provides power to load centers. The low voltage switchboards may or may not have bus-ties with other low voltage switchboards.
d. Sources are typically connected to a generator switchboard that may be configured to connect to either the port or starboard bus.

e. The port and starboard buses may be interconnected in several places to enable parallel operation. Typically, split plant operation is used such that the port and starboard buses operate independently.
f. All loads are powered by load centers or switchboards within the zone. Critical loads typically have a normal connection to a load center or switchboard powered from one bus (port or starboard), and an alternate connection to a load center or switchboard powered by the other bus.
g. The power system is designed to provide zonal survivability. In zonal survivability, damage and loss of two adjacent loads does not impact the ability to provide power (and other distributed system services) to the remaining undamaged loads. Generally, the port and starboard buses are protected such that even if the zone they are in is damaged, at least one of the two buses is likely to survive and function.

Figure 5 depicts an example of a low voltage zonal architecture and Figure 6 depicts an example of a medium voltage zonal architecture. Only a few loads are depicted; loads usually connect to load centers, but some may connect directly to a switchboard. For these examples, zone 1 is typically at the bow of the ship, and the zones are numbered in sequence going aft. The switchboards at the bottom of the figures comprise the starboard bus and the switchboards at the top of the figures comprise the port bus. For zonal systems, loads must connect to switchboards or load centers within their zone. While these examples show two load centers per zone, a zone may have more than two load centers.

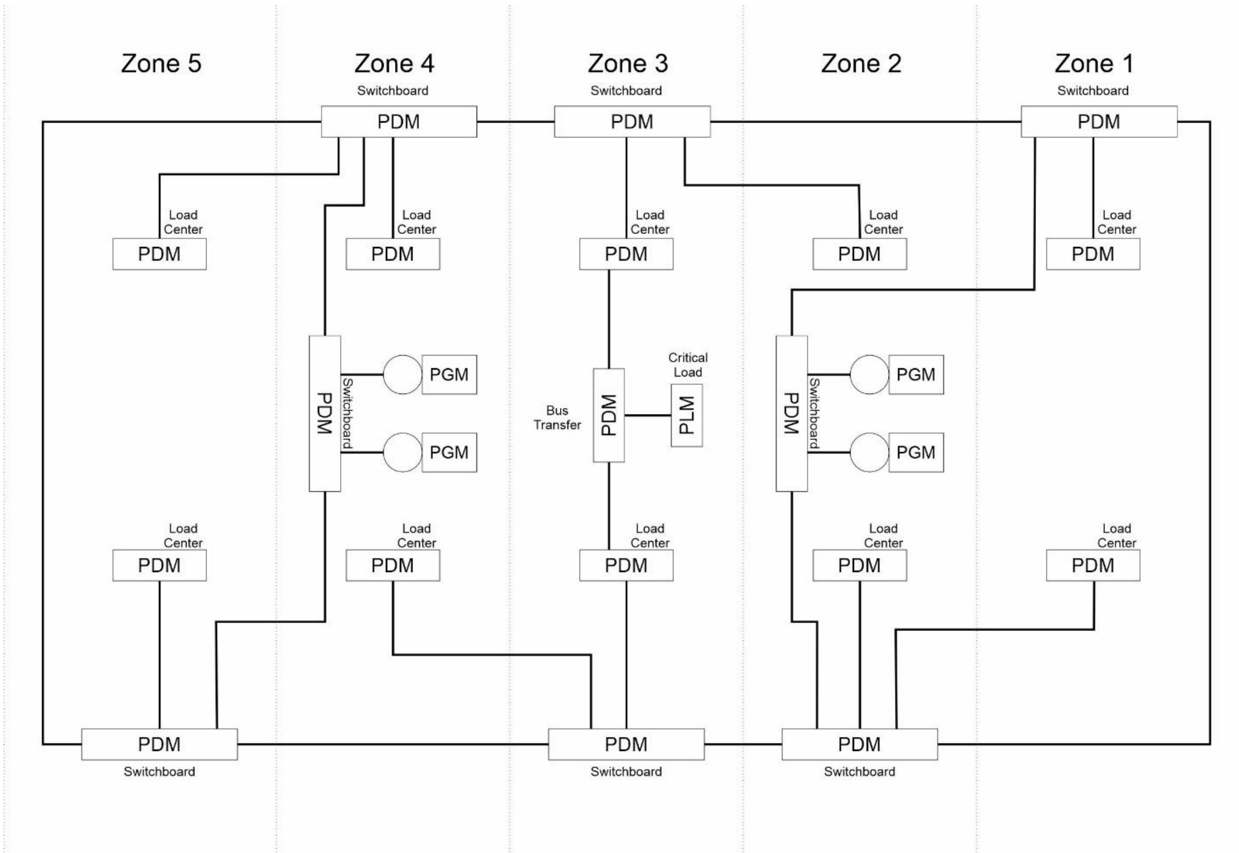


Figure 5 Example of a Low Voltage Zonal Architecture

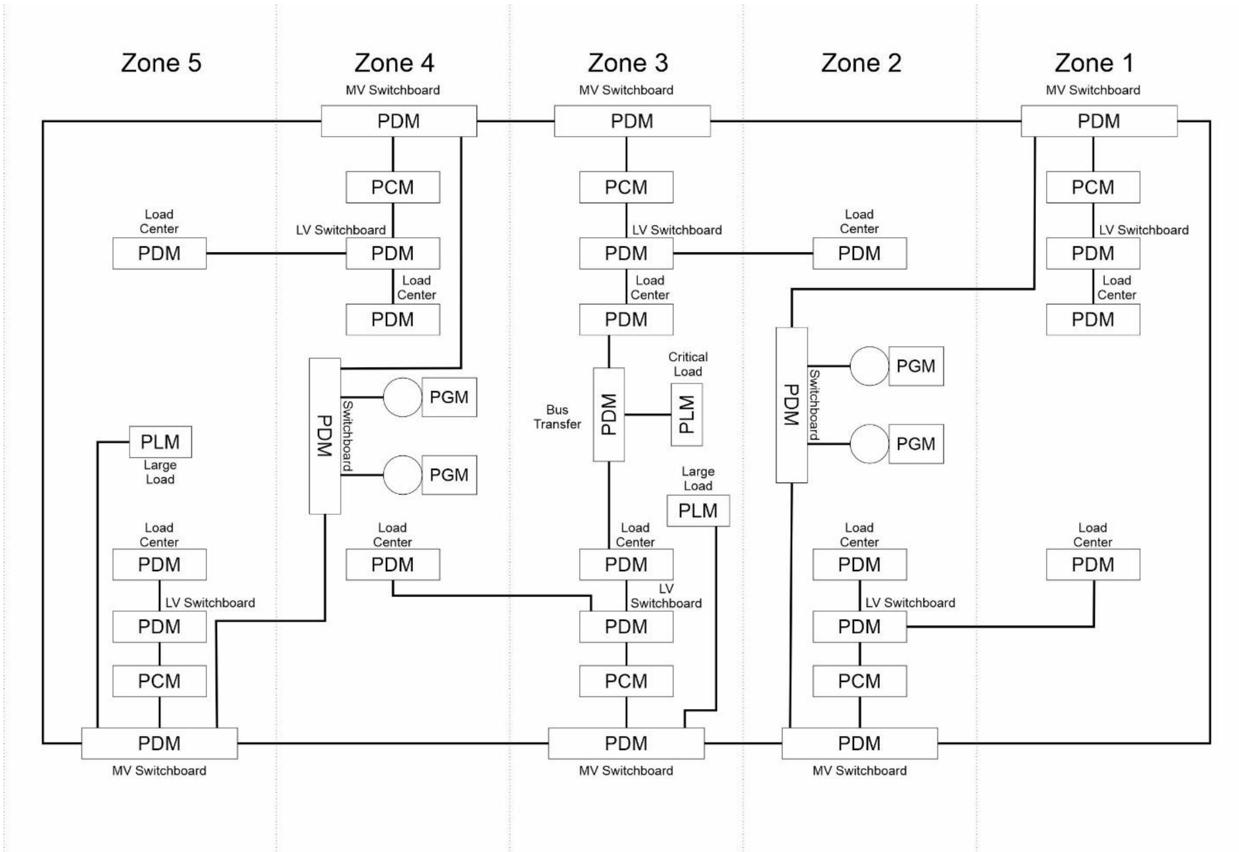


Figure 6 Example of a Medium Voltage Zonal Architecture

4. Propulsion System Architecture

   The building blocks of a propulsion system architecture are typically:

   a. Prime Movers
   b. Propulsion Motors (PMM)
   c. Reduction Gears (including clutches and turning gear)
   d. Shafting (including couplings and seals)
   e. Line and thrust bearings
   f. Propulsors (Typically propellers and waterjets)
   g. Stern tubes
   h. Struts

   These building blocks are used to implement the following types of propulsion system architectures:

   a. Mechanical Drive
   b. Hybrid Electric Drive
   c. Integrated Power Systems

d. Electric Drive

During the early stages of design, the line and thrust bearings, stern tubes, and struts may not be separately depicted; their presence is assumed. When these components become important to the types of analyses performed, they are then incorporated into the architecture.

See McCoy (2015) for further insights in propulsion system architectures.

4.1. Mechanical Drive

In a mechanical drive ship, prime movers are mechanically connected to a propulsor via a shaft, usually via a reduction gear. Prime movers are typically diesel engines or gas turbines. In the past, and for nuclear powered ships, steam turbines have been used. Older ships even used reciprocating steam engines. Propellers or other propulsors (such as waterjets) are used to convert the mechanical power on the shaft to the ship's forward motion.

Multiple prime movers may be connected to a single shaft via the reduction gear as depicted in Figure 7. If the prime movers are of different types (diesel engine or gas turbine) as depicted in Figure 8 then they are often called "combined plants." Common combined plants include:

CODAG Combined Diesel and Gas Turbine

CODOG Combined Diesel or Gas Turbine

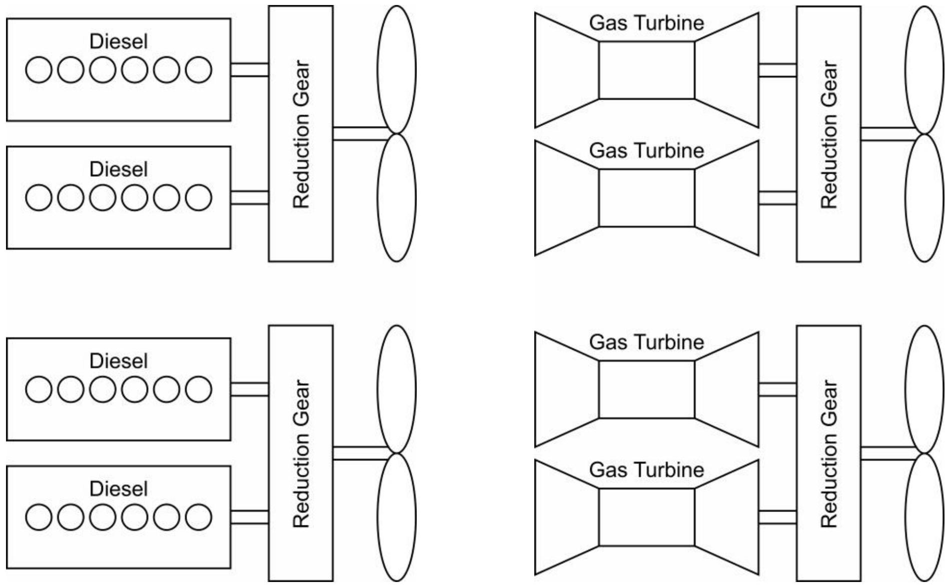
The "and" implies that the diesel and gas turbines are intended to operate at the same time; both contribute to the maximum propulsion power available.

The "or" implies that the diesel and gas turbine are not intended to operate at the same time; the diesel is typically used at low speeds and the gas turbine at high speeds. Only the gas turbine contributes to the maximum propulsion power available.

Combining gears may be employed to power multiple shafts from the same set of prime movers as depicted in Figure 9.

In some cases, most notably when slow speed diesel engines are employed as prime movers, the reduction gear is omitted and the engine output shaft is directly connected to the propeller shaft as shown in Figure 10.

On some ships, an electrical generator is integrated with the shaft or reduction gear as a Power Take-off (PTO) device to provide electrical power when the ship is underway.



(a) (b)

Figure 7 (a) Diesel Mechanical Drive (b) Gas Turbine Mechanical Drive

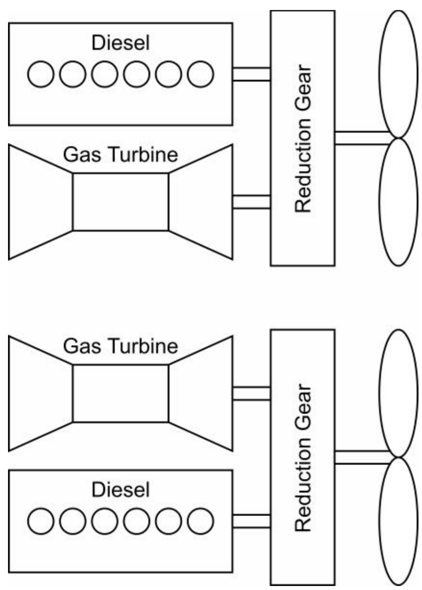


Figure 8 Combined Plant – CODAG or CODOG

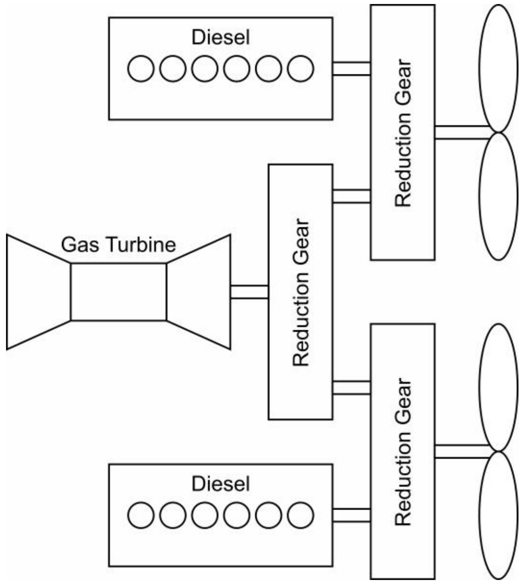


Figure 9 CODAG or CODOG with Combining Reduction Gear connected to Gas Turbine

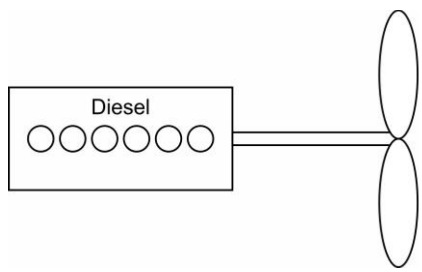


Figure 10 Low Speed Diesel with direct connection to propeller shaft

4.2. Hybrid Electric Drive

A hybrid electric drive is similar to mechanical drive with the exception that an electric motor is used in addition to a prime mover (usually a gas turbine or diesel engine). As depicted in Figure 11, the electric motor may be integrated into the reduction gear, or directly mounted on the propeller / propulsor shaft. The electric motor normally has an associated motor drive.

HEDs are typically used to improve fuel economy at low speeds; if the ship operates most of the time at low speeds, a hybrid electric drive often will prove to be more economical. For naval ships with an Anti-Submarine Warfare (ASW) mission, HED enables quieter operation when employing passive sonars at low speeds; thereby increasing the detection capability of the sonar.

The motor and motor drive can be designed to provide power only at low speeds in an “OR” configuration, or can be designed to provide power over the entire speed range by themselves or at higher powers, along with a prime mover in an “AND” configuration. The OR configuration is easier and less expensive to integrate. These configurations may be called:

CODLAG Combined Diesel Electric and Gas Turbine

CODLOG	Combined Diesel Electric or Gas Turbine
CODLAD	Combined Diesel Electric and Diesel
CODLOD	Combined Diesel Electric or Diesel

If the motor drive is capable of bi-directional power capability, the motor and drive may be configured to be able to provide power from the prime mover, through the motor (acting as a generator to produce electrical power) and drive, and into the PDM. This capability is often called Propulsion Derived Ship Service (PDSS).

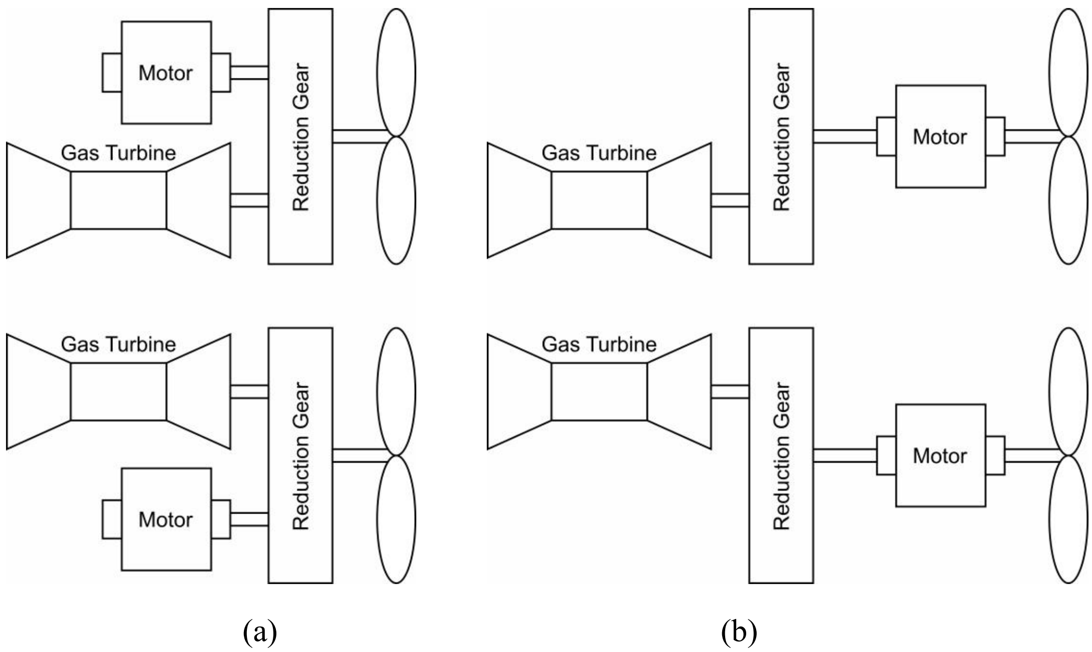


Figure 11 Hybrid Electric Drive (a) Motor integrated with reduction gear (b) Shaft mounted motor

4.3. Integrated Power System

In an integrated power system, all the prime movers generate electrical power for use by both ship service (hotel) loads (PLM) and propulsion motors (PMM). IPS maximize the flexibility of the power system; any prime mover can be used to provide power to either ship service loads (PLM) or propulsion (PMM). Because of the integration, IPS configurations typically have fewer prime movers than equivalent MD configurations. Additionally, IPS prime movers can often be operated more efficiently than MD prime movers. In an IPS system, the propulsion system begins with the interface of the PMM to the electrical power system at a PDM as depicted in Figure 12; typically, the power rating of the motor leads to a medium voltage connection.

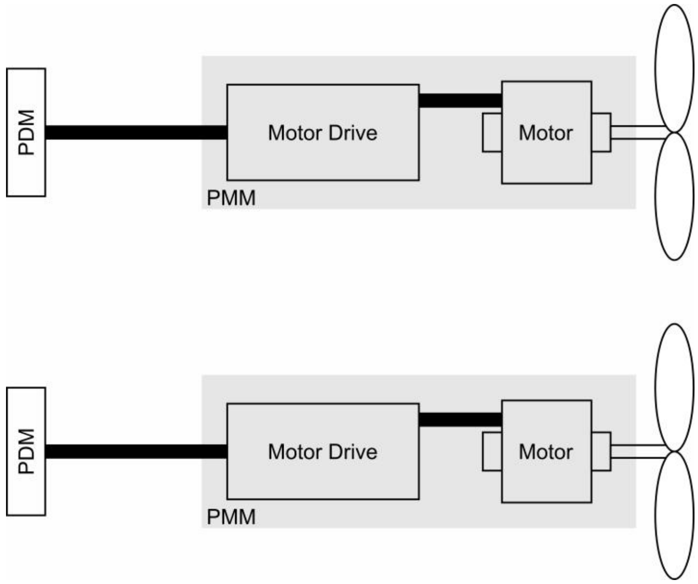


Figure 12 Integrated Power System Propulsion System

4.4. Electric Drive

An electric drive ship is similar to a mechanical drive ship with the exception that the reduction gear is replaced by propulsion generators, possibly motor drives, and propulsion motors. As depicted in Figure 13, the propulsion generators (PGM) are purely dedicated to propulsion (PMM); their power cannot be used for other ship service loads (PLM). Often motor drives are only used at low speeds and power levels; at higher speeds and power levels, the motor and generator are operated synchronously without a motor drive. When operating synchronously, the generator produces variable frequency AC power where the frequency is proportional to the shaft speed.

Although once common, electric drive architectures are rarely implemented in new construction ships. Electric drive systems are almost always less efficient than a mechanical drive system at high speed; and do not provide the benefits of integration of an IPS configuration. Electric drive does offer greater arrangement flexibility as compared to mechanical drive ships; for this reason, electric drive may prove advantageous in a future design.

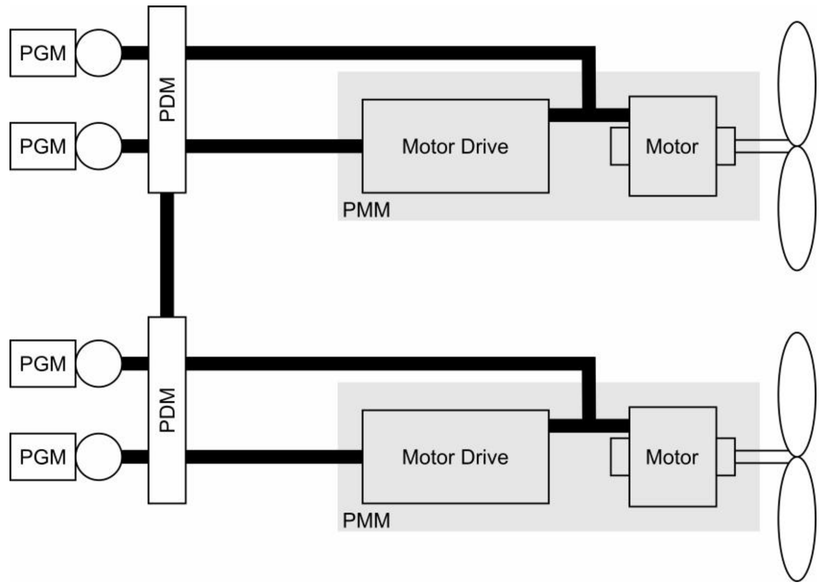


Figure 13 Electric Drive

5. Low voltage vs medium voltage buses

   Ships with a modest total electrical load (in the low MWs or less) typically generate and distribute power at low voltage (below 1 kV). At higher power levels, the unavailability of appropriate circuit breakers and other fault protection components, and the weight of the cables, generally precludes using low voltage generation. At the higher power levels, power is generated at medium voltage (generally between 1 kV and 13.8 kV or AC and 1 kV and 18 kV for DC). For AC power generation, ship service loads are usually powered via medium voltage to low voltage transformers via a low voltage switchboard connected to the transformer secondary. For DC power generation, ship service loads are powered via power electronic based PCMs.

6. AC vs DC power

   Most ship service loads (PLM) employ low voltage AC power. Regardless of whether power is generated at low voltage or medium voltage, or as AC or DC power, in the end, these loads still require low voltage AC power. Historically and even now, most ships with a modest total electrical load generate low voltage AC power to match the needs of the ship service loads; loads requiring even lower voltages are powered via low voltage transformers. Low voltage DC power generation is becoming more common due to being able to operate diesel generators (PGM) at optimal speeds for fuel economy, the availability of fault protection components (PDM), the ease of integrating energy storage (ESM), and the reduction in total power electronic equipment needed in IPS configurations. PCMs are used to produce the low voltage AC power required by the majority of ship service loads. For many types of smaller ships, 1 kV DC systems are increasingly becoming the preferred solution.

If the power demands are great enough to warrant medium voltage power generation, then AC power generation is typically employed. Medium voltage DC (MVDC) power generation (above 1 kV) and distribution still face technical immaturity. While prototypes of MVDC power equipment exist, a complete system solution currently is not available from industry. Industry is reportedly working on creating MVDC system solutions to obtain the benefits realized in LVDC installations on larger ships; once available, MVDC systems will likely be employed in a number of applications.

7. References

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