Power Distribution

Norbert Doerry

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1. Introduction

Power distribution safely transfers electrical power among the other elements of a power system. Power distribution systems implement the power system architecture for a ship. Power distribution components include switchboards, load centers, power panels, cable, bus duct, bus pipe, bus transfer switches, shore power connections, and grounding systems.

The objectives of the design and integration of a power distribution system include ensuring:

a. Power distribution components have sufficient capacity for the anticipated voltage and currents under normal operation
b. The power distribution system can detect line-to-line faults, and isolate the fault while continuing to supply power to as many loads as possible.
c. Quality of service requirements are met.
d. Survivability requirements are met.
e. Generators can be safely paralleled with each other and with shore connections.

Details on power distribution components are provided in EDQP SD-311 and Patel (2021).

2. Distribution components

2.1. Switchboards

Figure 1: Switchboard on USS Blue Ridge (LCC 19) (US Navy photo)

Switchboards contain large circuit breakers and controls. Power sources such as generator sets, transformer secondaries, and high-power power-converters typically connect to the distribution system at a switchboard. Switchboards connect to other switchboards via bus ties and supply power to directly connected load centers, power panels, and high-power loads. A switchboard may also be the normal or alternate supply to a bus transfer switch. As shown in Figure 1, switchboards are usually deck mounted and have a local human-machine interface to interact with the controls. In zonal systems, switchboards are usually employed to connect the in-zone load centers to the main (interzone) distribution bus.

AC switchboards usually do not include power electronic conversion; all of the interfaces to the AC switchboard have the same voltage, number of phases, and frequency.

DC switchboards on the other hand, may include power converters within the switchboard. The dc switchboard may include rectifiers for the generator sets, motor drives for thrusters and large pumps, inverters to power ship service three phase loads, and special interfaces for energy storage. Within the dc switchboard, the bus bars and bus ties to other dc switchboards employ dc; all other interfaces could be ac power of various frequencies, voltages, and number of phases.

2.2. Load centers

Figure 2: Load center on USS Cole (DDG 67) (US Navy photo)

Load centers contain large and medium size circuit breakers and limited controls. As shown in Figure 2, load centers are typically deck mounted and may have a human-machine interface. The controls are usually limited to implementing load shedding and in some cases, fault protection coordination. Load centers normally receive power from switchboards. Load centers provide power to large and medium sized loads as well as power panels for groups of small loads. A load center may also be the normal or alternate supply to a bus transfer switch. Smaller ships may not employ load centers; large loads and power panels may be directly powered from switchboards.

2.3. Power panels

Figure 3: Power Panels on USS Wisconsin (BB 64) and N/S Savannah (photos by Norbert Doerry)

As shown in Figure 3, power panels are typically bulkhead mounted and contain a dozen or more circuit breakers for controlling power to small loads. A power panel may also be the normal or alternate supply to a bus transfer switch. Power panels receive power from switchboards, load centers, the secondaries of distribution transformers, the output of a bus transfer switch, or the output of a power converter.

2.4. Cable

Figure 4: Electrical cables on Emerald Princess (photo by Norbert Doerry)

High power shipboard ac power systems typically use three conductor cable for three-phase power. High power shipboard dc power systems may use four conductor cable where 2 conductors are used for each phase; the phases are alternated in the cable to reduce magnetic emissions. Low power ac and dc systems typically use two conductor cable; some may have an additional equipment ground conductor for safety. When installing cable, thicker cables require a bigger bend radius to avoid damaging the cable; for this reason, power cables are usually limited to overall diameter of less than 3 inches. To achieve higher currents than a single cable can safely handle, multiple cables are connected in parallel. In ac applications requiring voltages above 1000 V, sets of three single conductor cables may be used to reduce the required number of terminations. The cable conductors are generally copper and the insulation is chosen so as to not emit hazardous gasses or significant smoke when subject to high heat or burned.

As shown in Figure 4, cables are often mounted in cableways. Cableways keep the cables organized, but may result in electromagnetic interface from radiated emissions on one cable being induced onto another cable. Generally, signal and instrumentation cables should not be installed in the same cableway as power cables. Tightly packing cables can lead to cables overheating and suffering from thermal degradation or damage.

Cables for use above 1000 V usually incorporate metallic shields around each insulated conductor and around the set of conductors (cable shield). The shields around the conductors are grounded on one end so that the electric field within the insulation is uniform; if not grounded, the localized electric field within the insulation may be large enough to damage the insulation. The overall cable shield is typically grounded on both ends to provide a path for common-mode currents that otherwise would flow through the hull.

An insulation monitoring system may be installed on the power system to determine if cable insulation degradation has occurred.

2.5. Bus duct / bus pipe

Figure 5: Cross section of insulated bus pipe (photos by Norbert Doerry)

Insulated bus pipe (IBP) can carry thousands of amps in a single conductor. Because IBP can have a very tight bend radius, it may be found in areas where high currents must be carried in areas with significant arrangements challenges. As shown in Figure 5, industry can currently provide single conductor IBP; multi-conductor coaxial conductor IBP is under development. The coaxial conductor IBP has the advantage of very low electromagnetic emissions; the magnetic fields from the coaxial conductors largely cancel each other out.

Insulated bus duct is similar to IBP in that large solid conductors are used. Bus duct differs in that the conductors are typically flat bars separated by air and enclosed in a metallic housing. Bus duct typically requires more volume than IBP, but otherwise has many of the same benefits.

2.6. Bus transfer switches

Figure 6: Automatic bus transfer on USS Midway (CV-41) (photos by Norbert Doerry)

Bus transfer switches enable selecting between a normal and alternate source of power for a load. Bus transfer switches are typically provided for mission critical loads. Manual bus transfer (MBT) switches enable a sailor to manually switch between the two sources. Automatic bus transfers (ABT) (see Figure 6) will automatically switch from the normal source to the alternate source upon loss of power on the normal source. Controllable bus transfers (CBT) are similar to an ABT but are also connected to the machinery control system to enable a remote watchstander or control system to monitor the bus transfer status and to determine the bus transfer logic. A static bus transfer (SABT) is an ABT that uses power electronic switches instead of mechanical switches to transfer the power source. SABTs can transfer the power in less than 5 ms for a 60 Hz power system.

2.7. Shore power connections

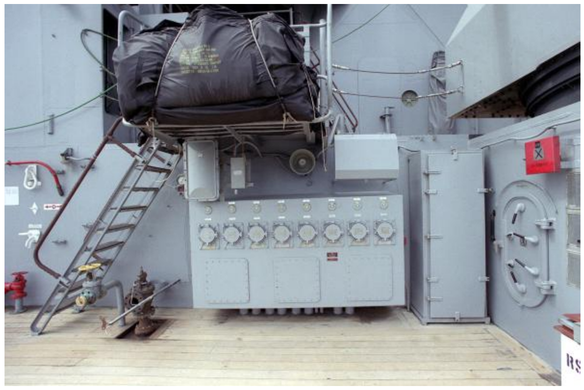

Figure 7: Shore power connection on USS Iowa (BB 61) (National Archives photo)

Figure 8: Shore Power Connection on USS Little Rock (LCS 9) (US Navy photo)

Naval ships and an increasing number of commercial ships employ shore power connections to power ships while inport. Figure 7 and Figure 8 show typical shore power connections for naval ships. Most naval ships employ 450 volts ac for the shore power connection. Multiple cables, each rated for 400 amps are connected between the ship and shore. Each connection is protected by a 400 amp circuit breaker.

Large ships that generate power above 1 kV may employ a high voltage shore power connection. For naval ships, standard shore power voltages are 4.16 kV and 13.8 kV. For commercial ships, standard shore power voltages are 6.6 kV and 11 kV.

2.8. Grounding system

Figure 9: Ground detection lamps on USS Slater (DE 766) (photo by Norbert Doerry)

The distribution system may include equipment to implement a grounding scheme such as grounding transformers and neutral grounding resistors. Ground detection lamps (Figure 9) are also used on ungrounded and high resistance grounded systems.

3. Cable selection

Power cables for shipboard use are selected based on the shipboard environment, ampacity, and voltage drop.

3.1. Shipboard use.

The shipboard environment places special demands on the design of power cables. A partial list of desired cable properties for use onboard ship include:

(a) Cables that penetrate watertight boundaries should themselves be watertight;
(b) Cables should be light weight;
(c) Cables should minimize the amount of smoke produced when subject to fire;
(d) Cables should not out-gas toxic substances under normal conditions and when exposed to fire;
(e) Cables should not degrade in a shipboard atmosphere including salt and petroleum products;
(f) Cables should have a reasonable bend radius to facilitate installation onboard ship;
(g) Cables should be undamaged during the installation process via cable pulling;
(h) Cables should be designed to last the service life of the ship.

3.2. Ampacity

Ampacity is the current carrying capacity of a cable; it is the maximum current a conductor can carry such that the temperature at the boundary between the conductor and the insulation is limited to a value that will not cause degradation of the insulation. Ampacity depends on both the temperature of the ambient air as well as how closely the cable is mounted to other current carrying cables. A load flow analysis is one method for determining the maximum amount of current that a cable is likely to carry. See Doerry (2025a) for details on load flow analysis. If the ampacity of a single cable is not sufficient for a particular application, multiple cables may be installed and connected in parallel. See Doerry (2025) for additional details and representative values of ampacity for different sized cables.

3.3. Voltage drop

If a cable is too long, even if the ampacity of the cable is not exceeded, the voltage drop from its connection to a switchboard, load center, or power panel to a served load may result in the voltage at the load to be outside of interface standard requirements. Voltage drop calculations are performed to determine if voltage drop is an issue. Doerry (2025) details how to perform these calculations and describes possible mitigations:

(a) Increasing size of conductors within the cable

(b) Power factor correction of loads

(c) Solid-state transformers and regulated power converters

(d) Adjustment of transformer secondary voltage

4. Circuit breakers

4.1. Fault protection overview

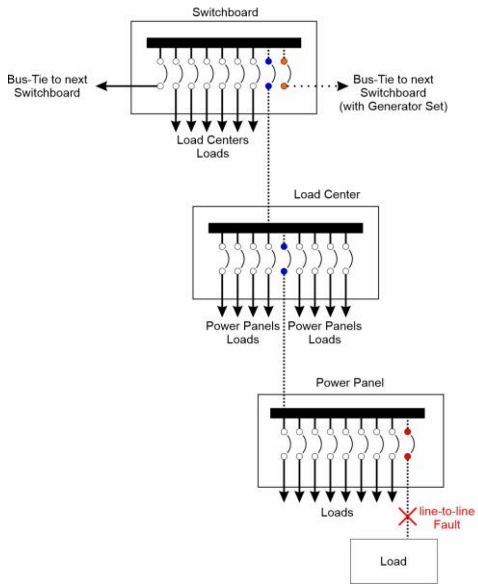

Figure 10: Fault protection

The purpose of fault protection in a power distribution system is to detect and isolate faults such that the supply of power is interrupted to a minimum number of loads. A fault protection system typically consists of circuit breakers, sensors, and possibly a protection relay. Figure 10 depicts a typical multi-layered distribution system. Generator sets insert power into the distribution system at the switchboard level; switchboards can also receive power from other switchboards via bus-ties. Switchboards provide power to load centers and large loads (and possibly power panels). Load centers provide power to loads and power panels. Power panels provide power to loads.

Should a line-to-line fault (short circuit) occur on the cable to a load as shown in Figure 10, then all the circuit breakers between the generator set and the breaker supplying the load will experience fault current. The goal of circuit breaker coordination is to only trip the circuit breaker immediately supplying current to the fault (circuit breaker in the power panel); thereby power will be cut to a minimum number of loads.

If in Figure 10, the line-to-line fault occurs on the cable between the load center and power panel (instead of between the power panel and load), only the circuit breaker in the load center supplying power to the faulted cable of the power panel should trip. This will cause a power outage for all loads connected to the faulted cable's power panel.

Faults on the bus-ties between switchboards require special treatment. Because power may normally flow in either direction through a bus-tie, protective relays are used to detect and locate the fault, then trip the appropriate breakers to minimize impact on the fewest number of loads.

4.2. Circuit breaker trip curves

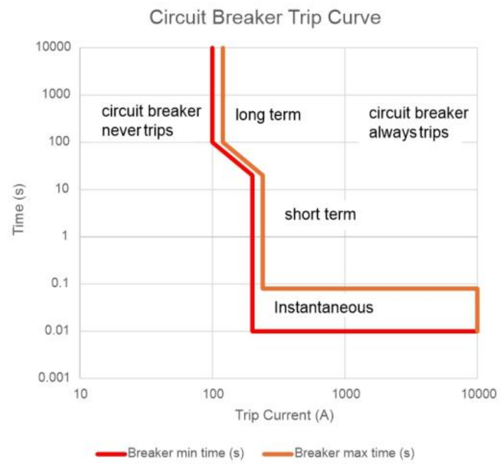

Figure 11: Circuit breaker trip curve

Figure 11 depicts a notional circuit breaker trip curve. The curve to the left and below represents the minimum time (vertical axis) that a circuit breaker will take to trip for the current level on the horizontal axis. The lowest current on this curve represents the rated current value for the breaker. The highest current on this curve represents the maximum current level the breaker can interrupt. If the current level for the corresponding time is always to the left or below this minimum time curve, then the circuit breaker should never trip. The curve to right and above represents the maximum time that a circuit breaker will take to trip; if the current level and duration is above this curve, the circuit breaker should always trip.

The circuit breaker trip curve has three regions: long term, short term, and instantaneous. The long term region is at the top and represents the current rating of the circuit breaker; if the current exceeds the associated current of the maximum time curve for a prolonged time, the circuit breaker should trip. The next region is the short term region. The current level to trip is a multiple (usually between about 5 and 10) of the long term current trip level. This region is intended to prevent the circuit breaker from tripping due to inrush current of transformers, capacitors, and motors and other transients. Finally, in the instantaneous region the circuit breaker does not wait; the circuit breaker clears the fault very quickly. The clearing time has a minimum and a maximum value.

4.3. Circuit breaker coordination

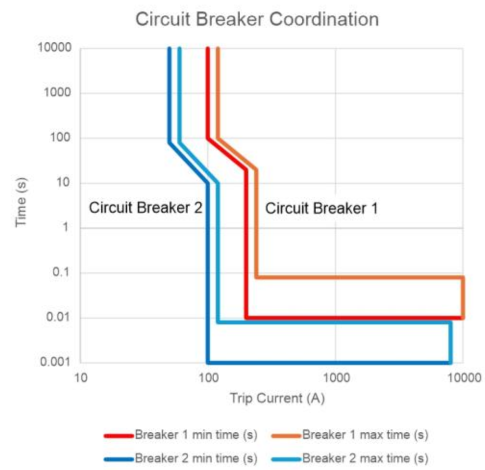

Figure 12: Circuit breaker coordination

Figure 12 superimposes the circuit breaker trip curves of a notional 50 amp circuit breaker (Circuit breaker 2) and a notional 100 amp circuit breaker (Circuit breaker 1). If we assume circuit breaker 2 is “downstream” of circuit breaker 1, then the two breakers are said to be coordinated because for any current level above the rated trip current for circuit breaker 2, the maximum time curve for circuit breaker 2 is less than the minimum time curve for circuit breaker 1. If a fault occurs downstream of circuit breaker 2, then it will trip and circuit breaker 1 will remain closed. If a fault occurs between the circuit breakers, then circuit breaker 1 will trip and circuit breaker 2 will remain closed.

If the minimum time curve for circuit breaker 1 is below the maximum time curve circuit breaker 2 for any portion of the curves, then the two circuit breakers are not coordinated. During a fault, the wrong circuit breaker, or both circuit breakers may trip.

While this example features only two circuit breakers, three or more circuit breakers may exist between the switchboard and the load. All of the circuit breakers in the path between the generator set and the load must be coordinated.

Some circuit breakers have the ability to adjust their trip curves so that the power system designer is better able to ensure the circuit breakers are coordinated.

5. References

EDQP SD-311 EDQP Study Paper Electrical Power Distribution

Doerry, Norbert, "Shipboard power system limiting load flow and load flow analysis", IEEE ESTS 2025, Alexandria VA, August 5-8, 2025. (2025a)

Doerry, Norbert, "Voltage Drop Calculations on Shipboard Power Systems", 16th International Symposium on Practical Design of Ships and Other Floating Structures PRADS 2025 Ann Arbor, MI, USA, October 19th - 23rd 2025. (2025)

Patel, Mukund, *Shipboard Electrical Power Systems*, CRC Press, Roca Raton 2021.

