Power Electronics Capacity Sizing

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April 25, 2026

1. Introduction

This document discusses determining the power rating and redundancy requirements of power electronic converters used to connect two different power distribution systems; it does not include power electronic converters that serve a single (or a few loads) such as propulsion motor drives and variable speed drives. Power electronic converters may have one or more "inputs" where the interface(s) adheres to either ac or dc specifications, and one or more "outputs" where the interface(s) adheres to either ac or dc specifications. AC to dc converters are usually called rectifiers, DC to ac converters are usually called inverters. In this context, ac to ac converters are often called frequency changers or solid-state transformers. DC to dc converters are generally called dc to dc converters or dc solid-state transformers. The Integrated Power Management Center (IPMC) specified by MIL-PRF-32272 is an example of a power electronic converter that may have multiple inputs and multiple outputs.

As compared to electromagnetic devices such as transformers and synchronous generators, power electronic converters normally have limited overload capability. A typical commercial inverter may have an overload rating on the order of twice the continuous rating for 3 seconds, or 1.6 times the continuous rating for 10 seconds. If the overload continues at too high of a level for too long, the inverter shuts down. This overload could be caused by supplying in-rush current, short circuits, cycling loads, or a number of other reasons.

In comparison, a synchronous generator is typically required to withstand providing current of magnitude I (per unit) for time t (seconds) where $I^2t = 180$ (MIL-DTL-3124). Thus for 3 seconds, the synchronous generator should be able to withstand providing 7.75 times the continuous rating; for 10 seconds, the synchronous generator should be able to withstand providing 4.24 times the continuous rating. These limits do not include being able to regulate the output voltage to within specification. The overload rating of MIL-DTL-3124 generators (providing regulated voltage) is 1.5 times rated current for 2 minutes. The I^2t rating is sufficient to handle most in-rush current demands and provide sufficient fault current to enable coordination of circuit breakers. The overload rating accommodates most cycling loads.

The rating for power electronic converter should be chosen to minimize the probability that the load will exceed the power electronic converter's maximum rating in the steady-state, and not exceed the overload ratings for the specified time intervals.

Power electronic converters may be a single monolithic converter; or may be composed of multiple modules that are paralleled to provide a combined power rating. Some converters, such as the IPMC, have input modules, an internal dc bus or multi-winding transformer, and output modules. These modular converters provide significant flexibility in configuring power electronic converters to meet specific application requirements.

Specific requirements for power electronic converters are provided by ABS MVR.

ABS MVR states:

> "Where transformers and/or converters form a part of the vessel's electrical system supplying to essential services and services necessary for minimum comfortable conditions of habitability, as defined in 4-8-1/7.3.3 and 4-8-1/7.3.4, the number and capacity of the transformers and/or converters is to be such that, with any one transformer or converter, or any one single phase of a transformer, out of service, the remaining transformers and/or converters or remaining phases of the transformer are capable of supplying power to these loads under normal seagoing conditions."

> "Semiconductor converters are to be rated for continuous load conditions and if required by the application, are to have specified overload capabilities."

2. Considerations

2.1. Load analysis

The traditional load factor analysis process for calculating the maximum operating load assumes that the variation of load around the mean value is small; the magnitude of each cycling load is assumed small with respect to the sum of all of the load averages. While this is generally true at the total ship level, power electronic converters only serve a subset of the ship's loads. Certain cycling loads may be significant; the traditional load factor analysis may underestimate the required power rating of the power electronic converter.

As detailed by Doerry and Amy (2019), employing the zonal load factor process as described in DPC 310-1 is recommended for calculating the maximum operating load for power electronic converters if a significant amount of the load served by the power electronic converter is due to cycling loads. Zonal load factors account for the variability in the total load due to having non-constant power loads. The zonal load factor method requires for each load: the load factor for the 24-hour average calculations; the connected load; and the peak load. The zonal load factor method will generally result in a larger operating load as compared to the traditional load factor method.

2.2. Margin and Service Life Allowance

Margins account for uncertainty in the operating load estimate during the design and construction of a ship; service life allowance accounts for growth in load while the ship is in-service. IEEE Std. 45.1 recommends the following margins and SLA:

Detail Design Margin: 5% for existing follow-on designs to 20% for new first-time designs

Construction Margin: 5% for existing follow-on designs to 20% for new first-time designs

SLA: 20% (1% per year for 20 years)

If the power electronic converter is designed to be modular where additional power capacity can be added in service, the SLA may be accommodated through having empty “slots” to add capacity as well as ensuring sufficient cooling and ensuring cables and cabinet backplanes have sufficient rating to handle the addition of capacity. The margin should be accounted for in the capacity installed during construction.

2.3. Quality of service and survivability

The failure rates and maintenance requirements of power electronic converters are such that redundancy is typically required to achieve quality of service (reliability) requirements. This redundancy may be at the total power converter level; or if the power converter is modular, may be provided through redundancy of modules. When modules are employed, instead of providing redundancy for the full power capacity of the converter, the redundancy is provided for only one of multiple modules paralleled to achieve the required power rating. Quality of service can be further improved by providing the modules with the capability for hot swapping. In hot swapping, modules may be replaced without shutting down the overall converter.

The rating of power electronic converters should account for both normal operation and for cases where additional load is applied via bus transfers from other converters that are not functioning. In this case, load shedding of lower priority loads may be required to supply all vital loads.

2.4. In-rush current

Electromagnetic-based loads such as transformers, motors, solenoids, and relays typically have large in-rush currents to establish the magnetic fields within their ferromagnetic cores. It is not unusual for these in-rush currents to be ten (or more) times the rated current for each load device and last ten to hundreds of milliseconds. Other loads may have large input filter capacitors that when first energized have an inrush current only limited by the effective series resistance (ESR) of the capacitor; the inrush current may be 20 times the rated current, but last for only milliseconds.

Selecting a power converter with sufficient power capacity but insufficient in-rush capacity is a common design error in shipboard power system design. Many times, the design error is not recognized until shipboard testing; correcting the error at this late stage can be very costly. For this reason, analyzing in-rush current during earlier stages of design is highly recommended.

A power electronic converter is likely able to supply sufficient inrush current if individual loads have power ratings less than 5% of the power electronic converter power rating and provisions are made to preclude multiple loads with large in-rush currents from starting at the same time. Options to mitigate possible problems due to in-rush current include:

- Use a starting resistor (or impedance) with each load having an in-rush current to limit the in-rush current. Bypass the starting resistor after the in-rush current has decayed with either a solid-state switch or a relay. Motors for example, may have resistors in series with the stator winding that are bypassed by a relay energized by a switch that detects when the motor has achieved a minimum speed.
- When starting a converter connected to an unenergized bus, ramp the voltage on the converter output slowly (soft starting) to reduce the magnitude of the in-rush currents.
- Use low-voltage protection (LVP) controllers for non-vital loads with an inrush current to avoid having multiple loads start at the same time. An LVP controller requires manual (or remote control) restart following a power interruption.
- For loads with input contactors, use a random delay between when power is applied to the load and when the input contactors are closed.
- Use pre-charge circuitry on specific loads to reduce or eliminate in-rush current. Pre-charge circuits energize the magnetic fields of electromagnetic devices or the input capacitors before the main power connection to the load is made.
- Use a power electronic converter with sufficient capacity to supply in-rush current to all loads that could simultaneously require in-rush current.

2.5. Fault protection

Traditional circuit protection implementations rely upon having sufficient fault current to selectively trip circuit breakers. Power electronic converters typically current limit during a fault; the amount of available fault current is thereby limited. For this reason, one must be careful when selecting circuit breakers for power distribution systems powered by power electronic converters. Circuit breakers should be chosen that will not trip due to in-rush current, but will selectively trip in the presence of a sustained overload or short-circuit.

If a traditional circuit protection implementation is at risk of not working, alternate strategies include:

- Flatten the distribution system by employing multiple output converters on the power electronic converter; each output converter supplies only one load center or power panel. The output converter serves as the first layer of circuit protection; a short-circuit on the output of one output converter should not impact the power quality of the outputs of the other output converters. Only one circuit breaker would exist between the power converter and individual loads; eliminating the need to coordinate circuit breakers.
- Use a differential protection relay. In differential protection, the power distribution system is subdivided into protection zones. The currents in each conductor are measured wherever they cross the protection zone boundary. These currents should,

by Kirchhoff's Current Law (KCL), sum to zero. If the sum of the currents exceeds a threshold, then the circuit breakers supplying power to the protection zone are tripped.

- Increase the power rating of the power converter until it is capable of producing sufficient fault current to selectively trip circuit breakers.

2.6. Efficiency

For many power electronic converters, the power losses often may be modeled by two terms: A constant term (no load losses), and a term proportional to the load current squared. (See Doerry and Parsons 2023)

$$P_{Loss} = P_{No\_Load\_loss} + R_{loss} I_{out}^2$$

Efficiency is the output power (P_{out}) divided by the input power ($P_{out} + P_{loss}$)

$$\eta = \frac{P_{out}}{P_{out} + P_{No\_Load\_loss} + R_{loss} I_{out}^2}$$

For dc systems where the output voltage is regulated to its nominal value, the efficiency may be restated as

$$\eta = \frac{\frac{P_{out}}{P_{rated}}}{\frac{P_{out}}{P_{rated}} + \frac{P_{No\_Load\_loss}}{P_{rated}} + \left(\frac{P_{rated} R_{loss}}{V_{out}^2}\right)\left(\frac{P_{out}}{P_{rated}}\right)^2}$$

In this form, $\frac{P_{No\_Load\_loss}}{P_{rated}}$ represents the no load losses as a fraction of the rated load; this value is often provided in datasheets. $\frac{P_{rated} R_{loss}}{V_{out}^2}$ represents losses that are a function of the power provided to the load. When a power converter is lightly loaded ($\frac{P_{out}}{P_{rated}}$ is small), then the losses are dominated by the no load losses. Across similar converters, $\frac{P_{No\_Load\_loss}}{P_{rated}}$ typically does not vary that much. This means that a power converter with a higher rating will likely have higher no load losses. For this reason, one should be careful not to select a power converter with a substantially higher rating than needed; the higher no load losses will probably result in lower efficiency when supplying P_{out}.

If the power converter uses multiple modules to achieve the desired power rating, it may be possible for the control system to turn some modules off when the load is low. In doing so, the no load losses are not incurred for the modules that have been turned off. In this way, the overall efficiency of the power converter may be improved.

2.7. Black start

As detailed in IEEE Std. 45.1, a black start is energizing an electrical system from either a dark ship or dead ship state. A dark ship occurs when all generator sets are offline, but energy storage is still available to power control systems and enable startup. A dead ship occurs when all generator sets are offline, and all energy storage (except that dedicated to emergency generator starting) is depleted.

One possible challenge to starting a power electronic conversion device is when it relies upon services that are powered by its output. An example could be if a liquid cooled power converter relies upon chilled water provided by a chill water plant that is powered by the power converter. The power converter may not be able to start until it senses that it has cooling water; the cooling water however, requires electrical power to operate the chilled water plant. For the dark ship condition, energy storage may be sufficient to initially power the chilled water plant to enable the power converter to startup and take over powering the chilled water plant. For the dead ship condition, the power converter may be rated to supply a fraction of its rated power for the time necessary to power up the chilled water plant to cool the power converter and enable it to operate at full load. The design should be analyzed to ensure the power system can startup following either a dark ship or a dead ship.

3. References

ABS MVR, ABS Rules for Building and Classing Marine Vessels

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

MIL-DTL-3124, Detail Specification, Generator, Alternating Current, 60-Hertz (Naval Shipboard Use)

MIL-PRF-32272, Performance Specification, Integrated Power Management Center (IPMC)

DPC 310-1 Electric Power Load Analysis (EPLA) for Surface Ships

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