Power Conversion

Norbert Doerry

October 26, 2025

1. Introduction

Power conversion equipment have two or more power system interfaces. Each interface can allow power to flow into it, power to flow out of it, or power to be able to flow in either direction. While in operation, power flows into at least one power system interface and flows out of at least one power system interface. The interface standard (to include voltage, frequency, number of phases, etc.) at each power system interface may be different; the ability to convert power of one type to power of another type is one of the major reasons for using power conversion.

Unless energy storage has been integrated into the power conversion equipment, the sum of the power flows into the interfaces equals the sum of the power flows out of the other interfaces plus internal losses of the power conversion equipment.

If the power conversion equipment is designed such that there is a very high impedance at or below line frequency between the conductors of one power system interface and the conductors of another power system interface, then the two interfaces are said to be isolated. Isolation is normally accomplished with a transformer; the transformer may be operated with the fundamental frequency at line frequency (50 or 60 Hz) or at much higher frequencies (kHz to MHz). A ground fault on one conductor of a power system interface will not significantly impact the line to ground impedance of an isolated power system interface.

Three broad categories of power conversion equipment can be found onboard ship: transformers, power electronic converters, and motor-generator sets. While this document provides an introduction to these equipment types, there are many texts available to provide details of their operation.

2. Transformer components

A transformer is one of the simpler forms of power conversion for ac distribution systems. A transformer is used to convert ac power of one voltage to ac power of another voltage; the frequency remains unchanged. As depicted in Figure 1, each power interface connects to one or more coils of wire around a laminated silicon steel core. Power transfer is via magnetic induction from one coil to another via the core. A transformer is inherently an isolated power converter. Although a transformer is also inherently bi-directional, convention has it that under normal conditions, power flows into the primary winding (normally at a higher voltage) and out of the secondary winding. Three-phase transformers with primary voltages below 1000 volts are usually constructed as a transformer bank consisting of three single-phase transformers as depicted in Figure 2. Other transformers, including those with primary voltages above 1000 volts may have all three sets of windings on the same transformer core; the three-phase transformer would be in a single enclosure.

Most transformers are air cooled; some transformers, particularly ones with high power ratings, have cooling fans to improve cooling by increasing air flow across the transformer.

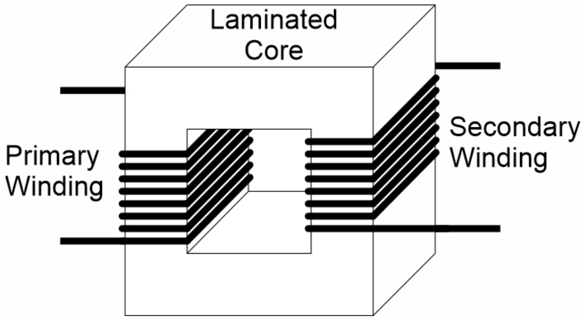

Figure 1: Single phase transformer

Figure 2: Transformer bank onboard USS Midway (CV-41)

Possible system integration issues with transformers include voltage regulation and fault current. For a transformer, regulation is the drop in voltage on the secondary from no-load to full-load divided by the secondary's nominal system voltage when the voltage on the primary is maintained at the primary's nominal system voltage. The regulation must be low enough so that the voltage at loads is within interface standard limits. However, reducing the regulation increases the available fault current on the secondary. If the regulation is too low, then the available fault current on the secondary may exceed the fault interruption capability of available circuit breakers.

3. Power electronic converter components

Power electronic converters employ semiconductor switches and other components to perform converter functionality. As depicted in Figure 3, specific names may be applied to converters based on the type of power at the input power interface and the at the output power interface. A power electronic converter that converts ac power to dc power is often called a rectifier. A power electronic converter that converts dc power to ac power is often called an inverter (Figure 4 depicts a prototype of an advanced 200 kW inverter). DC to dc converters may be called choppers, boost converters if the output voltage is greater than the input voltage, and buck converters if the output voltage is less than the input voltage. AC to ac converters are called frequency changers, cycloconverters, or simply converters. In many cases, a power electronic converter is composed of multiple stages to provide the necessary conversion functionality, and if necessary, isolation. For converters with ac at an input interface, the first stage may incorporate power factor correction circuitry. Figures 5-8 depict common multi-stage isolated power converter configurations. High frequency transformers are often incorporated to reduce the size, weight, and efficiency of the converter.

Power electronic converters may be either air cooled or liquid cooled. If liquid cooled, heat generating components are typically mounted to a cold plate that is cooled by fluid circulating in tubing embedding in the cold plate. Onboard ship, the cold plate may be directly cooled by freshwater or chilled water. Additives, such as glycol and corrosion inhibitors may be added to the freshwater. If air cooled, a circulating fan may be used to improve convective cooling.

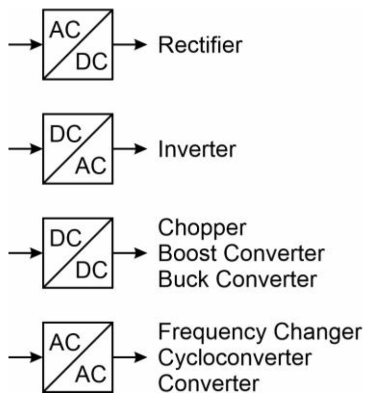

Figure 3: Converter types

(a)

(b)

Figure 4: 200 kW Inverter (a) Top view (b) Side view

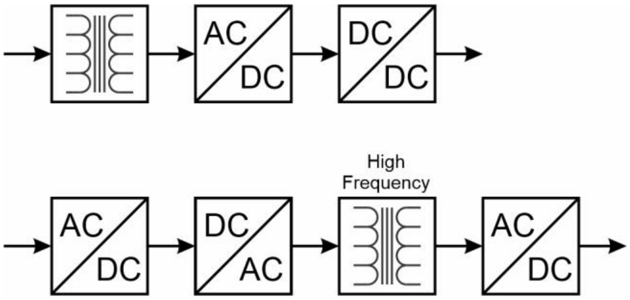

Figure 5: Multi-stage rectifiers

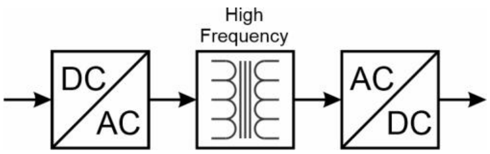

Figure 6: Multi-stage dc-dc converter

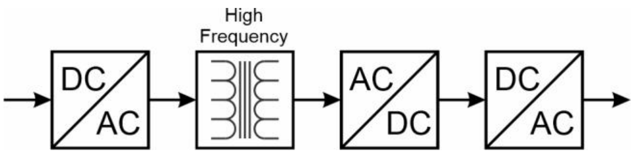

Figure 7: Multi-stage inverter

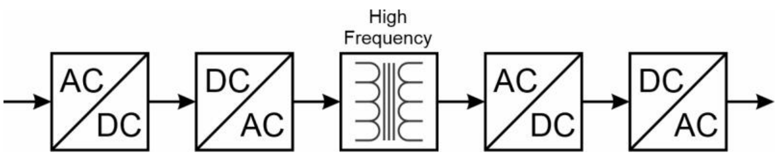

Figure 8: Multi-stage frequency changer

Filters are generally incorporated at each power interface of a converter to help ensure power at the interface adheres to the applicable interface standard. Common integration issues include non-fundamental frequency components of the input current waveform, common-mode voltages and currents, limited inrush capability on the output, limited fault current on the output. See Doerry and Amy (2024) for a more detailed description of possible integration challenges.

4. Motor-generator set components

Motor-generator sets were once a common method for converting ac power from one frequency (typically 60 Hz) to ac power of another frequency (typically 400 Hz). Most motor generator sets were rated below 200 kW. Although some motor generator sets are still in use, most have been replaced with power electronic converters. The maintenance costs associated with motor generator sets has been found to be higher than for power electronic converters.

Figure 9 depicts the components of a typical motor generator set. A motor controller uses power from the input cable to drive a motor at the speed necessary to produce the desired frequency on the generator. The motor shaft is directly connected to a generator shaft. The voltage regulator controls the excitation (field control) on the synchronous generator which produces power that is transferred to the power system via the output cable. The monitoring and control system coordinates the other components of the motor generator set and interacts with external control systems. Older designs may not have a monitoring and control system component.

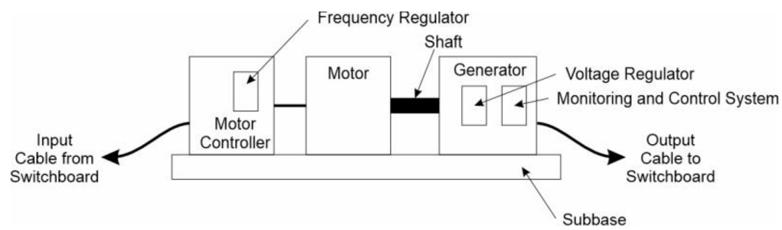

Figure 9: Motor-generator set components

5. Losses and Efficiency

The efficiency of a converter (η) is the output power divided by input power. The input power is thus the output power divided by the efficiency; this form is often used since we usually wish to determine the input power for a given load on the output. If the input power is non-zero at zero output power (no load input power), then the efficiency at 0 output power will be 0; one cannot use the efficiency to determine the no load input power. The presence of no-load input power will usually cause the efficiency curve to drop rapidly to 0 at low power levels, increasing the numeric errors in the input power calculations. Many datasheets will not even provide efficiency estimates below 25 to 50 per cent of rated power.

The no-load losses are generally due to energy required to magnetize an electromagnetic core (if the converter includes electromagnetic devices such as transformers, motors, or generators), cooling equipment (fans), and control equipment. Losses that are a function of output power are usually due to resistive loss within components, or the voltage drops in semiconductors.

If the losses are modeled directly, then the challenges associated with efficiencies may be mitigated. As described by Doerry and Parsons (2023) many times, the losses in converters may be successfully modeled by:

$$P_{Loss} = P_{noLoadLoss} + R_{loss} I_{out}^2$$

where:

P_{loss} = Losses in the converter (W)
$P_{noLoadLoss}$ = Losses at no load (W)
R_{loss} = Effective resistance for determining losses (ohms)
I_{out} = Output current (A)

For converters with a dc output, Doerry and Parson (2023) show that the efficiency can be stated as:

$$\eta = \frac{\frac{P_{out}}{P_{rated}}}{\frac{P_{rated} R_{loss}}{V_{out}^2}\left(\frac{P_{out}}{P_{rated}}\right)^2 + \frac{P_{out}}{P_{rated}} + \frac{P_{noLoadLoss}}{P_{rated}}}$$

where:

P_{out} = Output power (W)
P_{rated} = Rated Output Power (W)
V_{out} = Output Voltage

Data sheets may provide $\frac{P_{noLoadLoss}}{P_{rated}}$ and the efficiency ($\eta_{RatedPower}$) at rated power. The coefficient of the power squared term in the denominator can be calculated as:

$$\frac{P_{rated} R_{loss}}{V_{out}^2} = \frac{1}{\eta_{RatedPower}} - \left(1 + \frac{P_{noLoadLoss}}{P_{rated}}\right)$$

With this calculation, one can estimate either the losses or the efficiency for any output power. If more than one efficiency is provided in a datasheet, Doerry and Parsons (2023) demonstrate how to use the pseudo-inverse to provide estimates for $\frac{P_{noLoadLoss}}{P_{rated}}$ and $\frac{P_{rated} R_{loss}}{V_{out}^2}$. More detailed explanation on the use of the pseudo-inverse is given by Doerry and Bickel (2023).

For converters with three-phase ac outputs, the efficiency is calculated by

$$\eta = \frac{\frac{P_{out}}{S_{rated}}}{\frac{S_{rated} R_{loss}}{3V_{out}^2}\left(\frac{1}{PF}\right)^2\left(\frac{P_{out}}{S_{rated}}\right)^2 + \frac{P_{out}}{S_{rated}} + \frac{P_{noLoadLoss}}{S_{rated}}}$$

where:

S_{rated} = Rated Output Apparent Power (VA)
PF = Power Factor

If the efficiency is provided at several points, the pseudo-inverse can once again be used to estimate $\frac{S_{rated}R_{loss}}{3V_{out}^2}$ and $\frac{P_{noLoadLoss}}{S_{rated}}$. With these two estimates, the losses at any output power of a converter with a three-phase ac output can be determined:

$$\frac{P_{Loss}}{S_{rated}} = \frac{P_{noLoadLoss}}{S_{rated}} + \frac{S_{rated}R_{loss}}{3V_{out}^2}\left(\frac{S_{out}}{S_{rated}}\right)^2$$

where:

S_{out} = Output Apparent Power (VA)

See Doerry and Parsons (2023) for guidance on estimating coefficients for the losses withinr transformers, converters, motors and generators. For converters and generators, the losses at each stage of conversion can be estimated and then summed.

6. References

Doerry, Armin W., and Douglas L. Bickel, " Notes on Regression Analyses for Radar Parameter Estimation," Sandia Report SAND2023-12630, Sandia National Laboratories, February 2023.

Doerry, Norbert, and Mark A. Parsons, "Modeling Shipboard Power Systems for Endurance and Annual Fuel Calculations," SNAME J Ship Prod Des (2023)

Doerry, Norbert and John V. Amy Jr., "Integrating Power Electronic Equipment into Shipboard Power Systems", SNAME Maritime Convention 2024, Norfolk VA, October 15-16, 2024