# Power Conversion

## Shipboard Power System Fundamentals

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Dr. Norbert Doerry

# Essential Questions

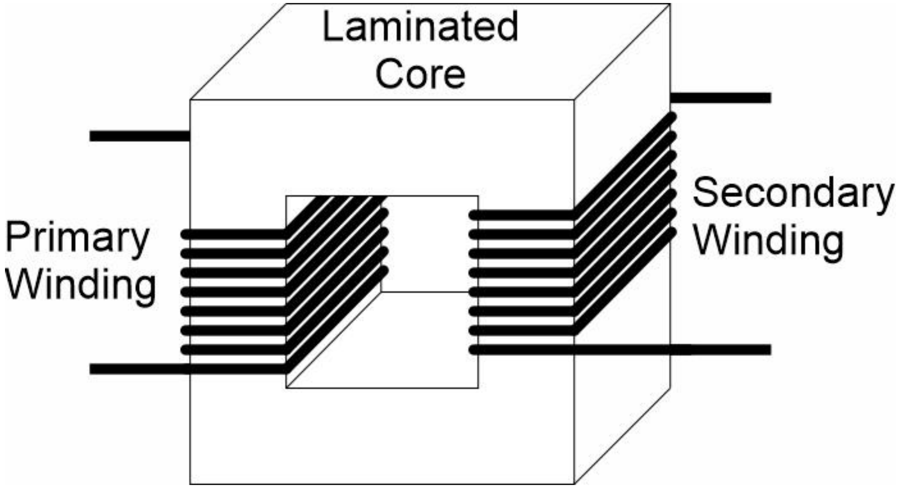
| | |
|---|---|
| What types of power conversion equipment are used onboard ship and why? | Understand |
| What components comprise power conversion? | Remember |
| What are the sources of losses in power conversion? | Understand |
| How are losses calculated using an efficiency curve? | Apply |

# Introduction

- Power conversion equipment have two or more power system interfaces
- Each interface may allow power to …
  - Flow in exclusively
  - Flow out exclusively
  - Flow in either direction
- Power balance
  - Power flowing in = Power flowing out + Internal losses + Power flowing into internal energy storage – Power flowing out of internal energy storage
- Types
  - Transformers
  - Power electronic converters
  - Motor Generator Sets

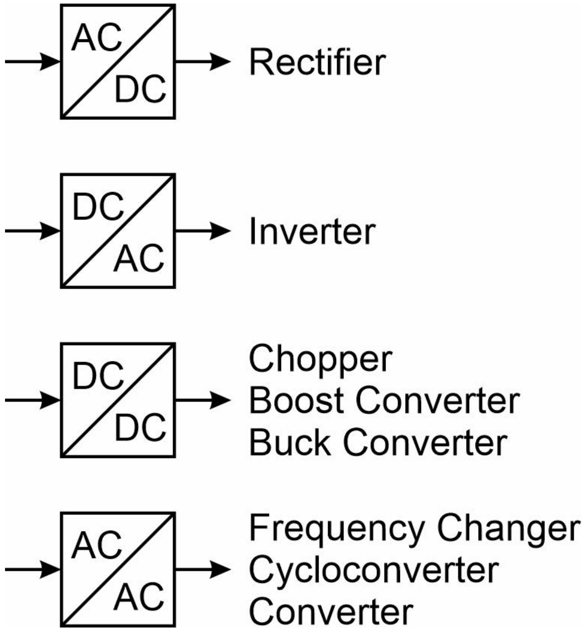

# Transformers

- Simple form of power conversion for a.c. systems.
  - Input and output voltages may be different.
  - Provides isolation between the primary and secondary winding.
    - Ground faults on one winding do not result in ground fault on the other winding.
    - Limits common-mode currents between primary and secondary windings.
- Three phase transformers often created by interconnecting three single phase transformers.
- System Integration issues
  - Voltage regulation – Secondary voltage drops as load increases
    - Can result in excessive voltage drop at loads.
  - Fault current – Secondary fault current can be very large.
    - May exceed interrupting capability of secondary circuit breakers.



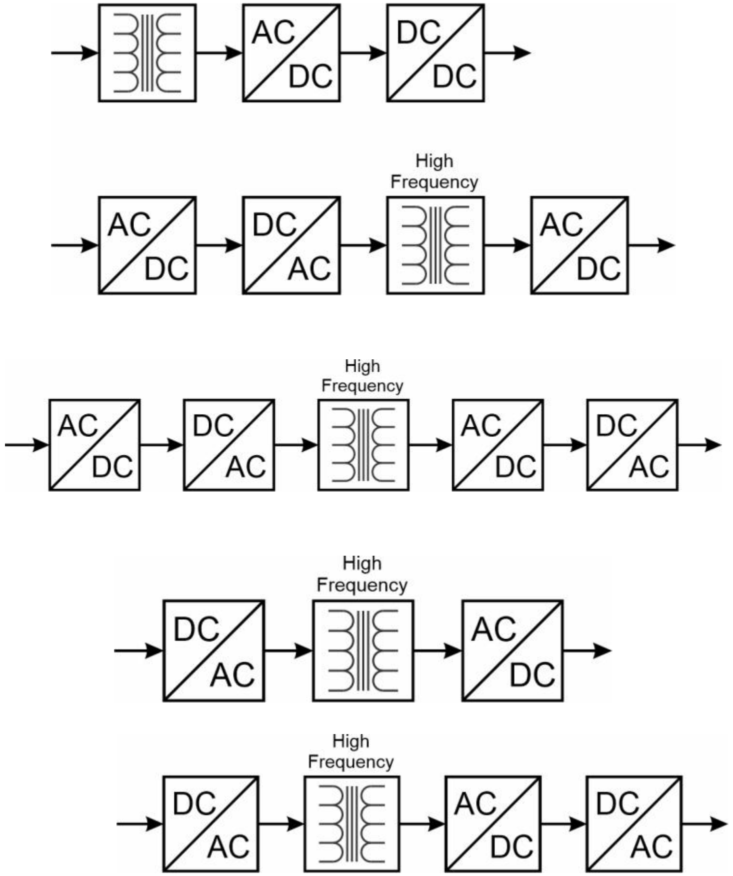

# Power Electronic Converters


- Rectifier
  - Converts a.c. to d.c.
- Inverter
  - Converts d.c. to a.c.
- Chopper, Boost Converter, Buck Converter
  - Converts d.c. to d.c
- Frequency Changer, Cycloconverter, converter
  - Converts a.c. to a.c.



# Multi-Stage Power Electronic Converter Topologies

- Usually used to provide isolation between the input and power terminals
  - Limits extent of ground faults.
  - May limit common mode currents.
- High Frequency Transformers  decrease space and weight; and are usually more efficient than 60 Hz transformers
  - But usually require additional power electronics that reduce efficiency and require space and weight.

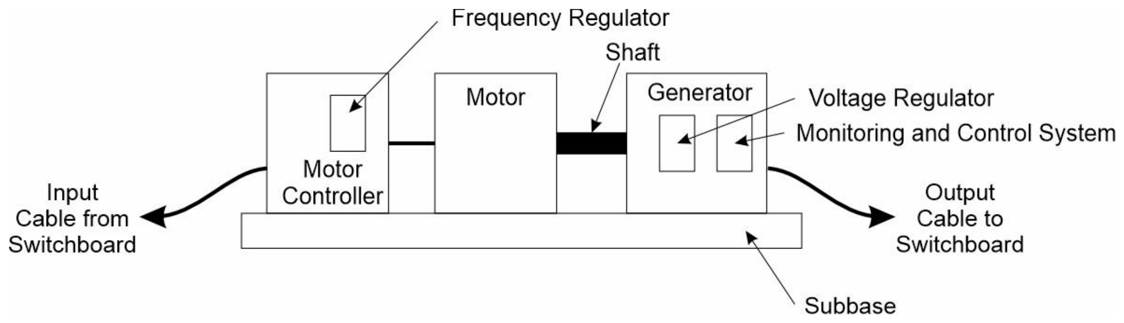


# Power Electronic Converter Integration

- Efficiency
  - Part load efficiency should be accounted for in system calculations.
- Cooling.
  - Liquid cooling may require additional systems.
- Frequency content of input current waveforms.
- Common mode voltages and currents.
- Limited inrush current capability at output.
  - May require soft starting of loads or use of variable speed drives.
- Limited fault current capability at the output.
  - May require special fault protection strategy.

# Motor Generator

- Once common, now mostly replaced by power electronic converters
  - 60 Hz to 400 Hz Frequency Changer.
- Components
  - Motor Controller with Frequency Regulator
  - Motor
  - Generator
  - Voltage Regulator
  - Monitoring and control system
  - Subbase



# Losses and Efficiency

- No load losses.
  - Magnetize electromagnetic cores.
  - Cooling components (such as fans).
  - Control equipment.
- Losses associated with output power.
  - Resistive losses of components.
  - Voltage drops across semiconductors.
- Efficiency is equal to the output power divided by input power.
  - Efficiency is usually 0 at zero load due to no load losses.
  - The efficiency vs output curve is very nonlinear at low power levels.
  - Efficiency is usually only provided in datasheets at several power levels (typically for output power levels above 50% of rated power).
  - Estimating efficiency below 50% of rated power usually requires extrapolation and is prone to error.

# D.C. output converter efficiency extrapolation

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

$P_{loss}$ = 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)

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

$P_{out}$ = 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.

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

If the data sheet does not provide $\frac{P_{noLoadLoss}}{P_{rated}}$

but does provide the efficiency at several output power, then the pseudo-inverse may be used to develop estimates for:

$$\frac{P_{noLoadLoss}}{P_{rated}} \text{ and } \frac{P_{rated} R_{loss}}{V_{out}^2}$$

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

# A.C. output converter efficiency extrapolation

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

where:

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

PF = Power Factor

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

where:

$S_{out}$ = Output Apparent Power (VA)

If efficiency is provided at several points, pseudo-inverse can be used to determine

$\frac{S_{rated}R_{loss}}{3V_{out}^2}$ and $\frac{P_{noLoadLoss}}{S_{rated}}$.

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