Modeling Shipboard Power Systems for Endurance Fuel and Annual Fuel Calculations

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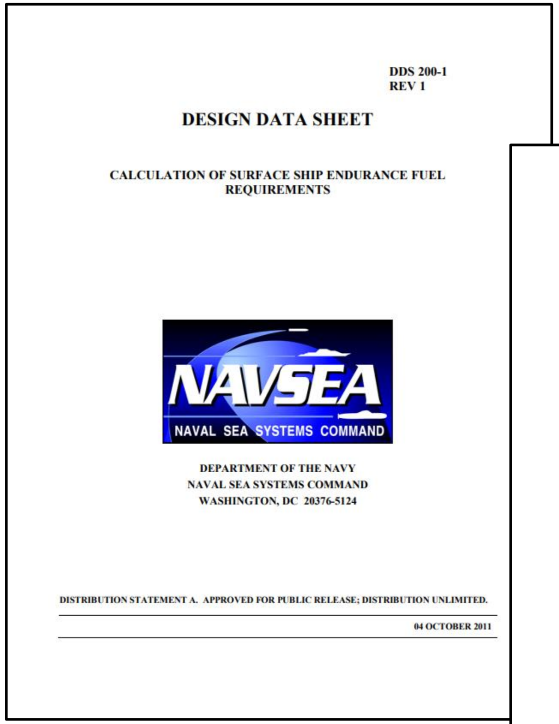
Background

- Endurance Fuel Requirements
  - Establishes required size of Fuel Tanks
  - Process defined in DPC 200-1
- Annual Fuel Usage, Annual Energy Cost, and Fully Burdened Cost of Energy
  - Used for lifecycle cost estimates
  - Process defined in DPC 200-2
- Both require modeling a ship's power and energy networks.
  - Steady state operation



DDS 200-1
REV 1

DESIGN DATA SHEET

CALCULATION OF SURFACE SHIP ENDURANCE FUEL REQUIREMENTS

NAVSEA
NAVAL SEA SYSTEMS COMMAND

DEPARTMENT OF THE NAVY
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WASHINGTON, DC 20376-5124

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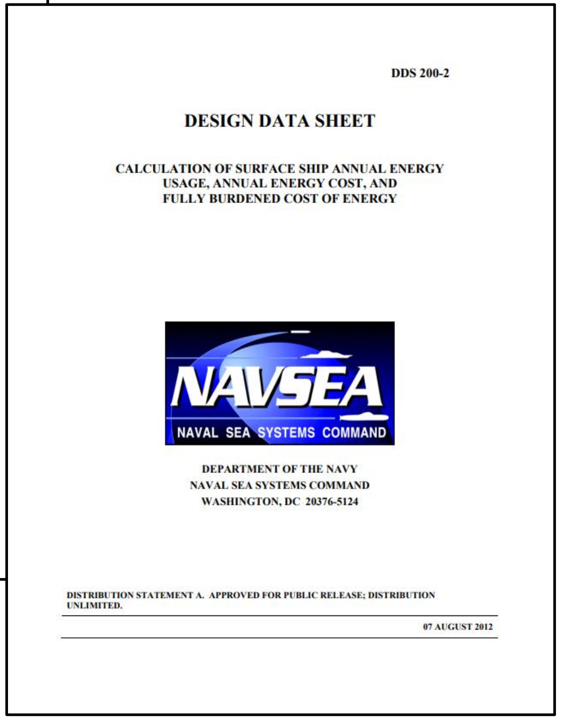

DDS 200-2

DESIGN DATA SHEET

CALCULATION OF SURFACE SHIP ANNUAL ENERGY USAGE, ANNUAL ENERGY COST, AND FULLY BURDENED COST OF ENERGY

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Agenda

- Endurance Fuel Calculations
- Annual Fuel Calculations
- Three Phase Power Introduction
- Modeling Process
- Modeling Efficiency
- Modeling Fuel Rate
- Modeling Components
- Electrical Power System Concept of Operations
- Propulsion System Concept of Operations
- Modeling Systems
- Run Matrix
- Post Processing Results
- Summary

Analysis Process

- Identify the operational conditions / ship states and ambient conditions.
- For annual fuel usage, define the operational modes, operational profile, and ship state participation table.
- Identify the ship's speeds required by the analysis.
- Define the power and propulsion architecture
- Define the electrical loads for the operational conditions and ambient conditions.
- Define the propulsion loads for the ship's speeds previously identified.
- Define efficiency and sfc curves for all power system and propulsion system components.
- Define electrical system and propulsion system concepts of operation.
- Develop an analysis model for calculating a combined fuel rate for a given set of system parameters, ship speed, operational condition, and ambient condition.
- Develop a "run matrix" with rows holding configuration data for the analysis model for every desired combination of system parameters, ship speed, operational condition and ambient condition
- Execute each row of the run matrix and record the fuel rates of the prime movers and the total fuel rate.
- Post process the fuel rates to determine the required size of fuel tanks or the estimated annual fuel usage.

Endurance Fuel Calculations

- Purpose: Determine required fuel tank volume
- Requirements
  - Economical Transit
    - Distance and speed
  - Surge to theater
    - Distance and sustained speed
  - Operational Presence
    - Operational Mission
    - Speed time profile
    - Operational presence time
  - Conditions
    - Ambient condition profile
    - Operating area for calculating seat state and fouling factor.

- Design Details
  - Electric Power Load Analysis (EPLA)
  - Electrical generation, conversion, and distribution efficiencies
  - Electric Plant Concept of Operations
  - Propulsion Plant Concept of Operations
  - Propulsion Speed-Power Curve
  - Propulsion motor module efficiency (electric drive)
  - Reduction gear efficiency (mechanical drive)
  - Prime mover specific fuel consumption curves
  - Plant deterioration allowance
  - Sea State and fouling factor
  - Tailpipe allowance

Annual Fuel Calculations

- Purpose: Determine how much fuel is estimated to be consumed in a year (and its cost)
- Requirements
  - Operational Profiles
    - Table of ship states
    - Operational mode list
    - One or more ship deployment and employment profiles
    - Ship State participation Table
  - Fully Burdened Cost of Energy
- Design Details
  - Those needed for DDS 200-1

Ship States

Operational Modes

Ship State participation Table	Inport – shore	Underway – Economic al Transit	Underway – Surge to Theater	Underway – Mission
Maintenance and Modernization	0.9	0.05	0.0	0.05
Predeployment Training	0.6	0.2	0.0	0.2
Deployment	0.1	0.2	0.0	0.7
MCO	0.05	0.15	0.05	0.75

Ship deployment and employment profiles

	Low OPTEMPO (fraction of time)				**High OPTEMPO (fraction of time)**			
Year	**Maintenance and Modernization**	**Predeployment Training**	**Deployment**	**MCO**	**Maintenance and Modernization**	**Predeployment Training**	**Deployment**	**MCO**
1	0.25	0.25	0.5	0.0	0.25	0.25	0.5	0.0
2	0.25	0.25	0.5	0.0	0.25	0.25	0.5	0.0
3	0.25	0.25	0.5	0.0	0.25	0.25	0.5	0.0
4	0.25	0.25	0.5	0.0	0.25	0.25	0.5	0.0
5	0.25	0.25	0.5	0.0	0.25	0.25	0.5	0.0
6	0.25	0.25	0.5	0.0	0.25	0.25	0.5	0.0
7	0.25	0.25	0.5	0.0	0.25	0.25	0.5	0.0
8	1.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0
9	0.25	0.25	0.5	0.0	0.25	0.25	0.5	0.0
10	0.25	0.25	0.5	0.0	0.25	0.25	0.5	0.0

Fuel Rate calculations

Both Endurance Fuel Calculations and Annual Fuel Calculations require calculation of overall fuel rate for a given operational condition and ambient condition.

- Requires modeling of
  - System Architecture
  - Loads (EPLA)
  - Propulsion speed – power curve
  - Efficiency of power conversion equipment
  - Fuel rates for prime mover as function of delivered power (sfc)
  - Electrical System Concept of Operations
  - Propulsion System Concept of Operations

Three phase voltage and currents Balanced Operation

Assume voltages and currents in the form:

$$V_A = \frac{\sqrt{2}}{\sqrt{3}} V_{ll} \sin(\omega t + \theta_V)$$

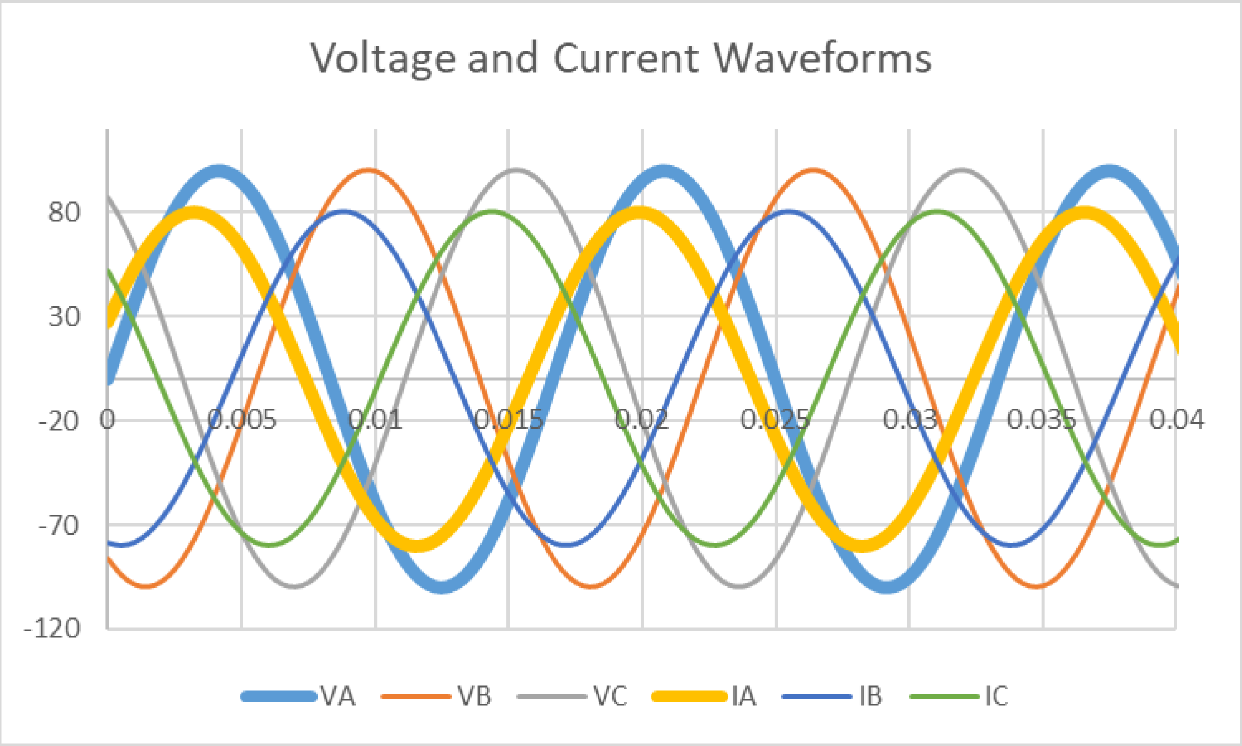
$$V_B = \frac{\sqrt{2}}{\sqrt{3}} V_{ll} \sin\left(\omega t + \theta_V - \frac{2\pi}{3}\right)$$

$$V_C = \frac{\sqrt{2}}{\sqrt{3}} V_{ll} \sin\left(\omega t + \theta_V + \frac{2\pi}{3}\right)$$

$$I_A = \sqrt{2} I_{phase} \sin(\omega t + \theta_I)$$

$$I_B = \sqrt{2} I_{phase} \sin\left(\omega t + \theta_I - \frac{2\pi}{3}\right)$$

$$I_C = \sqrt{2} I_{phase} \sin\left(\omega t + \theta_I + \frac{2\pi}{3}\right)$$



Then all six waveforms can be represented as

V_{ll}, θ_V — Phasor

I_{phase}, θ_I — Phasor

ω — Constant

Power for one phase / three phases

$$P_{inst} = VI$$ ← One phase

$$P_{inst} = \frac{\sqrt{2}}{\sqrt{3}} V_{ll} \sin(\omega t + \theta_V) \sqrt{2} I_{phase} \sin(\omega t + \theta_I)$$

$$P_{inst} = \frac{2}{\sqrt{3}} V_{ll} I_{phase} (\cos(\omega t)\sin(\theta_V) + \sin(\omega t)\cos(\theta_V))(\cos(\omega t)\sin(\theta_I) + \sin(\omega t)\cos(\theta_I))$$

$$P_{inst} = \frac{2}{\sqrt{3}} V_{ll} I_{phase} (\cos(\omega t)\sin(\theta_V)\cos(\omega t)\sin(\theta_I) + \cos(\omega t)\sin(\theta_V)\sin(\omega t)\cos(\theta_I) + \sin(\omega t)\cos(\theta_V)\cos(\omega t)\sin(\theta_I) + \sin(\omega t)\cos(\theta_V)\sin(\omega t)\cos(\theta_I))$$

$$P_{inst} = \frac{2}{\sqrt{3}} V_{ll} I_{phase} \left((\cos(\omega t))^2 \sin(\theta_V)\sin(\theta_I) + \cos(\omega t)\sin(\omega t)(\sin(\theta_V)\cos(\theta_I) + \cos(\theta_V)\sin(\theta_I)) + (\sin(\omega t))^2 \cos(\theta_V)\cos(\theta_I)\right)$$

$$P_{inst} = \frac{2}{\sqrt{3}} V_{ll} I_{phase} \left(\frac{1}{2}(\cos(2\omega t) + 1)\sin(\theta_V)\sin(\theta_I) + \frac{1}{2}\sin(2\omega t)(\sin(\theta_V - \theta_I)) + \frac{1}{2}(-\cos(2\omega t) + 1)\cos(\theta_V)\cos(\theta_I)\right)$$

If you time average over one cycle, then the $\cos(2\omega t)$ and $\sin(2\omega t)$ terms integrated to zero

$$P_{ave+1cycle} = \frac{2}{\sqrt{3}} V_{ll} I_{phase} \left(\frac{1}{2}\sin(\theta_V)\sin(\theta_I) + \frac{1}{2}\cos(\theta_V)\cos(\theta_I)\right) = \frac{1}{\sqrt{3}} V_{ll} I_{phase} \cos(\theta_V - \theta_I)$$

Now multiple by 3 for all three phases

$$P_{3phase\_ave} = \sqrt{3} V_{ll} I_{phase} \cos(\theta_V - \theta_I)$$ ← Real part of $\sqrt{3} V_{ll} I_{phase}^*$

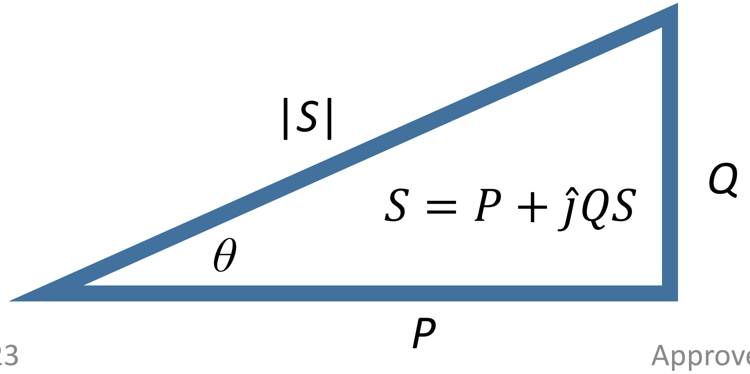
Electrical Power Relationships

Direct Current (DC)

- Scalar Quantities (W)
- Relationship to Voltage and Current

$$P = VI$$

Note:
- The magnitude of S is often called the Apparent Power.
- S as a complex number is also called Apparent Power. Also called Complex Power.



3 Phase Alternating Current (AC)

- Complex Quantities

$$S = P + \hat{j}QS = |S|\angle\theta$$

$$|S| = \sqrt{P^2 + Q^2} \qquad \theta = \text{atan2}(Q, P)$$

- Units:
  - |S| = Apparent Power (VA)
  - θ = Phase Angle (radians or degrees)
  - P = Real Power (W) (sometimes called Active Power or True Power)
  - Q =Reactive Power (VAR)
- Relationship to Voltage and Current

$$S = \sqrt{3}VI^*$$

  - V is line to line rms voltage (complex number)
  - I is rms phase current (complex number)
  - I^* is the complex conjugate of I
- Power Factor

$$Power\ Factor = \frac{P}{|S|} = \cos(\theta)$$

Mechanical and Fluid Power Relationships

Rotational Mechanical

$$P = T\omega$$

Where

P = Mechanical Power (W)

T =Torque (N-m)

ω = rotational speed (rad/s)

Heat transfer of fluid

$$P = \dot{m} c_p \Delta T_k$$

Where

P = Power (W)

$\dot{m}$ = mass flow rate (kg/s)

c_p = heat capacity at constant pressure (J/kg-K)

ΔT_k = change in temperature

Power due to change in pressure of fluid

$$P = Q\Delta p = \dot{m}\ \frac{\Delta p}{\rho}$$

Where

Q = volume flow rate (m^3/s)

Δp= change in pressures at terminals (Pa)

ρ = mass density (kg/m^3)

Time Scale of Interest

- Models generally are not accurate over all scales of time.
- Need to understand the time scale of interest
  - Things that are much slower are assumed to be constant
  - Things that are much faster are assumed to change instantaneously
    - Often ignore initial conditions
  - Things that are periodic over a time scale faster than of interest are treated as average values over the period.
- In electrical systems.
  - Power is usually considered an average over one cycle.
  - Time scale of interest must be greater than one cycle (16.7 ms)
- Analyzing pulsed power systems requires a different form of modeling than endurance or annual fuel calculations.
- Fuel calculation time scales of interest are on the order of a day.
  - Loads are averaged over a 24 hour cycle.

Level of fidelity of modeling

- Real Power only – electrical only
  - Historical Method
  - Spreadsheet models
  - DC Electrical Power Flow Solvers
- Add Reactive Power + Propulsion
  - AC Electrical Power Flow Solvers
- Add Chill Water impacts
  - AC Plant electrical load calculated based on operating condition
  - Multi-domain power flow solvers
- Add Seawater Cooling impacts
  - Seawater pump load calculated based on operating condition
  - Multi-domain power flow solvers

- Navy Tools
  - Excel based spreadsheets
    - Acceptable for Real Power only
  - S3D
    - Currently able to model "Real Power only"
    - Near term "add Reactive Power + Propulsion"
    - Far Term "add Chill Water impacts" and "Seawater Cooling Impacts"

FOCUS OF THIS PRESENTATION

Modeling Efficiency

- Losses in electrical equipment can often be modeled as:

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

- Efficiency is equal to output power divided by input power

$$\eta = \frac{P_{out}}{P_{out} + P_{noLoadLoss} + R_{loss} I_{out}{}^2}$$

- The output power is equal to

DC: $P_{out} = V_{out} I_{out}$

3 phase AC: $P_{out} = \sqrt{3} V_{out} I_{out} (PF)$

Efficiency cannot be used to determine no load losses

- For DC equipment:

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

- For 3 Phase AC equipment:

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

- If the terms in **red** are known, then the efficiency can be calculated for an arbitrary P_{out} (and PF for AC).
  - $\mathbf{R_{loss}}$ not normally provided in data sheets
  - $\mathbf{P_{noLoadLoss}}$ may be provided (or not)

Modeling Efficiency

- Normally, efficiency is provided at a few power levels. This data can be used to curve fit to estimate the terms in red.

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

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

- These can expressed in matrix format

$$Ax = B$$

And solved using pseudo-inverse

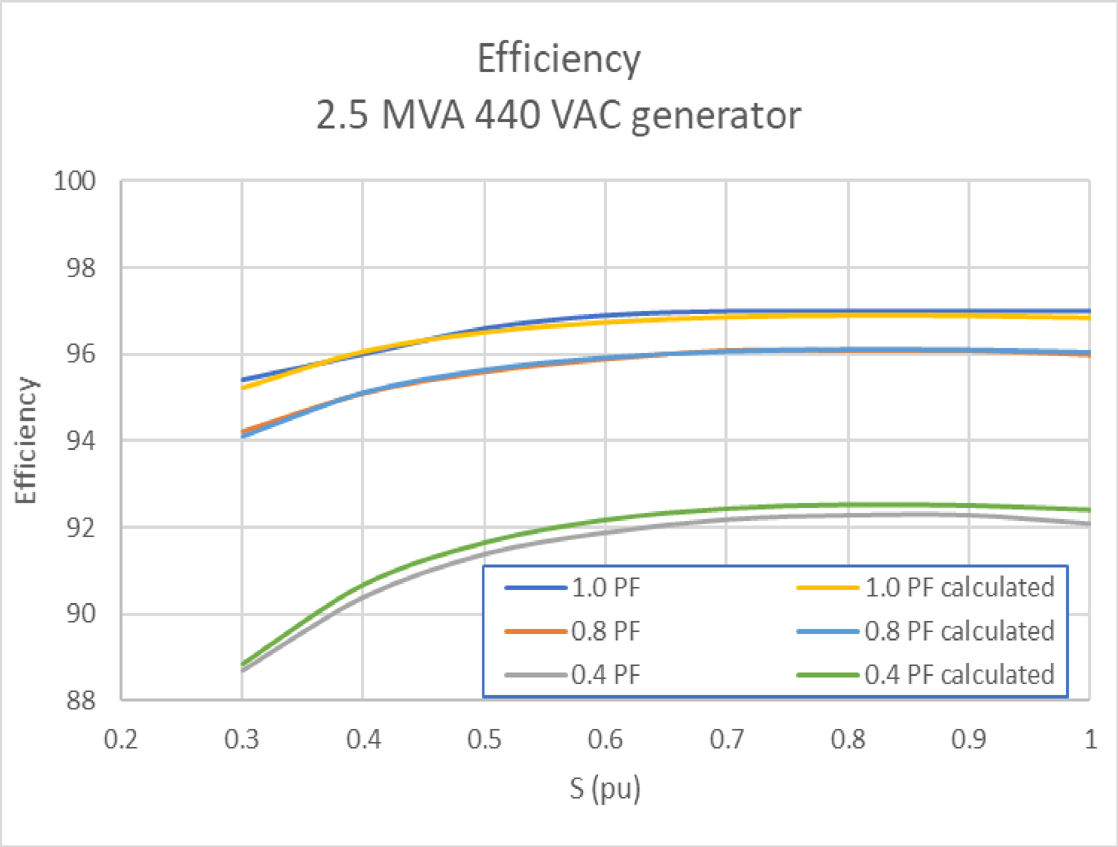
$$x = (A^T A)^{-1} A^T B$$

- For DC

$$x = \begin{bmatrix} \left(\frac{P_{rated}R_{loss}}{V_{out}^2}\right) \\ \left(\frac{P_{noLoadLoss}}{P_{rated}}\right) \end{bmatrix}$$

$$A = \begin{bmatrix} \left(\frac{P_{out}}{P_{rated}}\right)^2_1 & 1 \\ \left(\frac{P_{out}}{P_{rated}}\right)^2_2 & 1 \\ \left(\frac{P_{out}}{P_{rated}}\right)^2_3 & 1 \\ \left(\frac{P_{out}}{P_{rated}}\right)^2_4 & 1 \\ \cdots & \cdots \\ \left(\frac{P_{out}}{P_{rated}}\right)^2_n & 1 \end{bmatrix} \quad \begin{bmatrix} \frac{P_{out}}{P_{rated}}\left(\frac{1}{\eta} - 1\right)_1 \\ \frac{P_{out}}{P_{rated}}\left(\frac{1}{\eta} - 1\right)_2 \\ \frac{P_{out}}{P_{rated}}\left(\frac{1}{\eta} - 1\right)_3 \\ \frac{P_{out}}{P_{rated}}\left(\frac{1}{\eta} - 1\right)_4 \\ \cdots \\ \frac{P_{out}}{P_{rated}}\left(\frac{1}{\eta} - 1\right)_n \end{bmatrix}$$

Example: 2.5 MVA 440 VAC 60 Hz Generator



- Coefficients calculated based on data sheet (ABB)

$$x = \left| \begin{matrix} \left(\frac{S_{rated} R_{loss}}{3 V_{out}{}^2} \right) \\ \left(\frac{P_{noLoadLoss}}{S_{rated}} \right) \end{matrix} \right| = \left| \begin{matrix} 0.01947 \\ 0.01331 \end{matrix} \right|$$

Modeling losses instead of efficiency

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

For ac systems, assume V_{out} is a constant

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

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

For ac systems,

- Losses are a function of Apparent Power magnitude
- Efficiency is a function of Real Power magnitude and phase angle (or power factor)

Modeling Fuel Rate

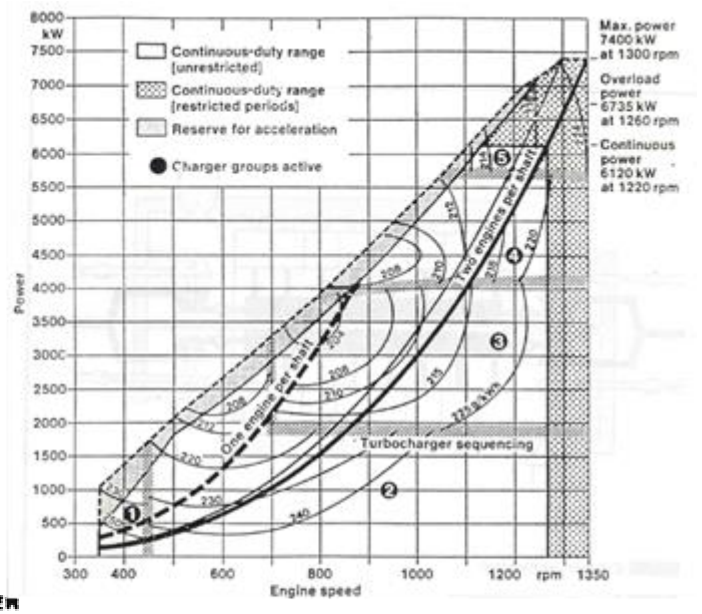
- Fuel rate usually specified in the form of specific fuel consumption (SFC)

$$FuelRate = (sfc)P_{out}$$

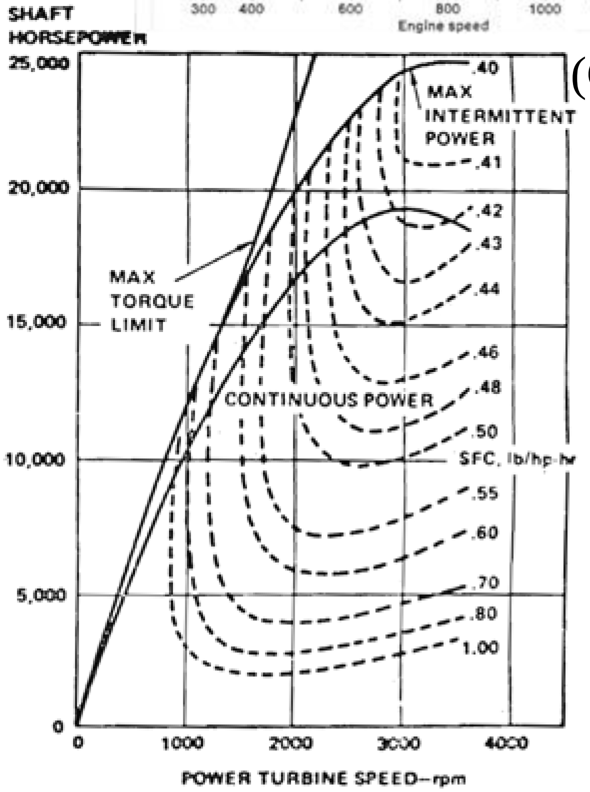
- The output power is mechanical for a prime mover. (gas turbine or diesel)
- The output power is electrical for a generator set.
- SFC for a prime mover is a function of output power and shaft speed.
  - SFC map desirable, but not often available.
- SFC typically provided for a few output power levels (normally > 50% rated power)
- SFC not useful for predicting idle power
- To extrapolate to lower power levels, suggest curve fitting the fuel rate, then calculating associated SFC

$$FuelRate = r_3 {P_{out}}^3 + r_2 {P_{out}}^2 + r_1 P_{out} + r_0$$

- Fuel Rate is often nearly linear with respect to output power.
- Use pseudo inverse to curve fit provided points.



(Guenther 1989)



(USNA 1979)

Splines

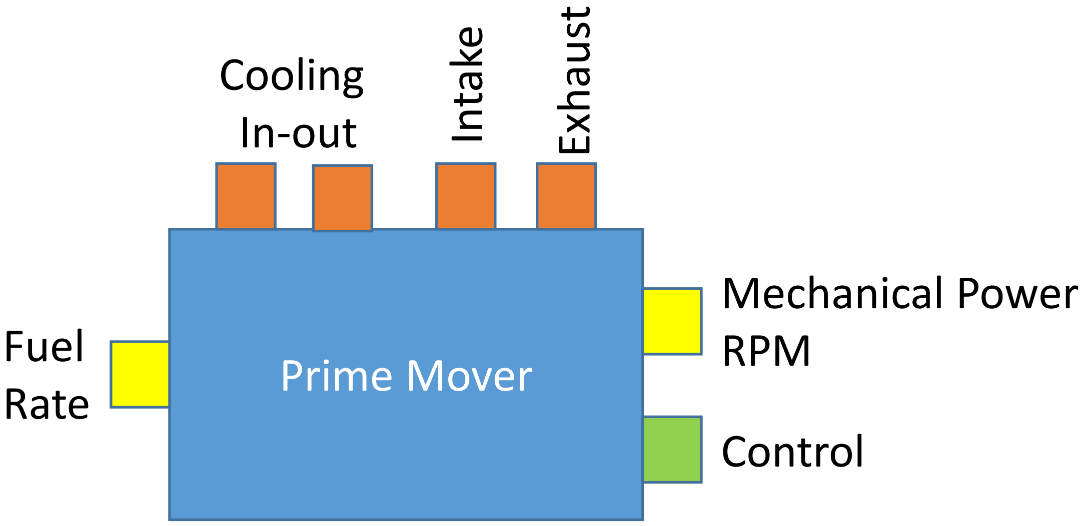
- Efficiency and SFC are hard to extrapolate directly from provided data
  - Efficiency is zero at zero output power
  - The reciprocal of efficiency is applied to output power – it tends to infinity as one approaches zero output power.
  - SFC is applied to output power – it tends to infinity as one approaches zero output power.
- Losses are nearly quadratic as a function of output current (or S)
- Fuel rate is nearly linear as a function of output power.
- Extrapolating losses and fuel rate are more likely to accurate with splines than efficiency and SFC

Modeling Components

- Prime Movers
- Reduction Gears
- Propellers and Shafting
- Generators
- Generator Sets
- Transformers
- Rectifiers
- Inverters
- Propulsion Motor Drives
- Propulsion Motors
- Multi-Port Power Conversion
- Energy Storage
- Ship Service Loads
- Cables

Prime Movers

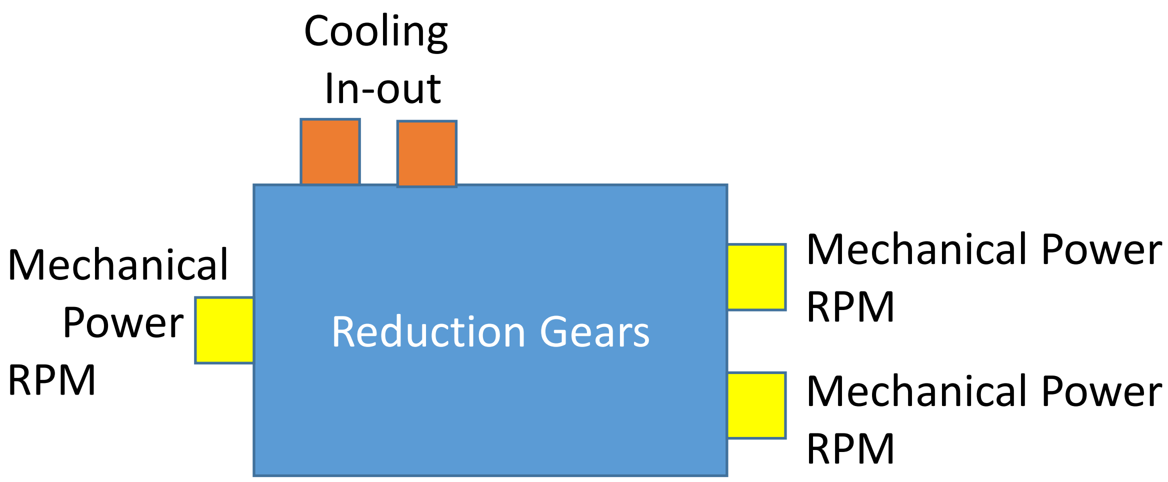
- Primary Interfaces
  - Fuel Rate (kg/s)
  - Mechanical Power (Power / RPM)
- Secondary Interfaces (generally do not model)
  - Cooling (temperature, kg/s)
  - Intake / exhaust (temp, m^3/s)
- Control Interface
  - Depends on system implementation
- Primary Properties
  - Rated Power
  - SFC Curve
  - Rated Speed
  - Online



Fuel rate depends on SFC curve and Mechanical Power out

Reduction Gears

- Primary Interfaces (3 times)
  - Mechanical Power (Power / RPM)
- Secondary Interfaces (generally do not model)
  - Cooling (temperature, kg/s)
- Control Interface
  - none
- Primary Properties
  - Rated Power
  - Efficiency curve
  - Rated Speed for each Mechanical Power interface



RPM ratios must match reduction ratio
Sum of power into reduction gear minus losses must be zero
Losses based on (n: RPM, P: power)

$$\frac{P_{Loss}}{P_{outRated}} = k_n \frac{n_{out}}{n_{outRated}} + k_P \frac{P_{out}}{P_{outRated}}$$

Based on data provided by Mowers (1992), the range of losses for a marine double reduction gear can be approximated by:

High Efficiency:	$k_n = 0.004866$	$k_P = 0.01036$
Low Efficiency:	$k_n = 0.007686$	$k_P = 0.01272$

Propellers and Shafting

- Primary Interfaces
  - Mechanical Power (Power / RPM)
- Secondary Interfaces (generally do not model)
  - none
- Control Interface
  - Ship Speed
- Primary Properties
  - Shaft Speed vs Ship Speed curve
  - Shaft Power vs Ship Speed curve
  - Online

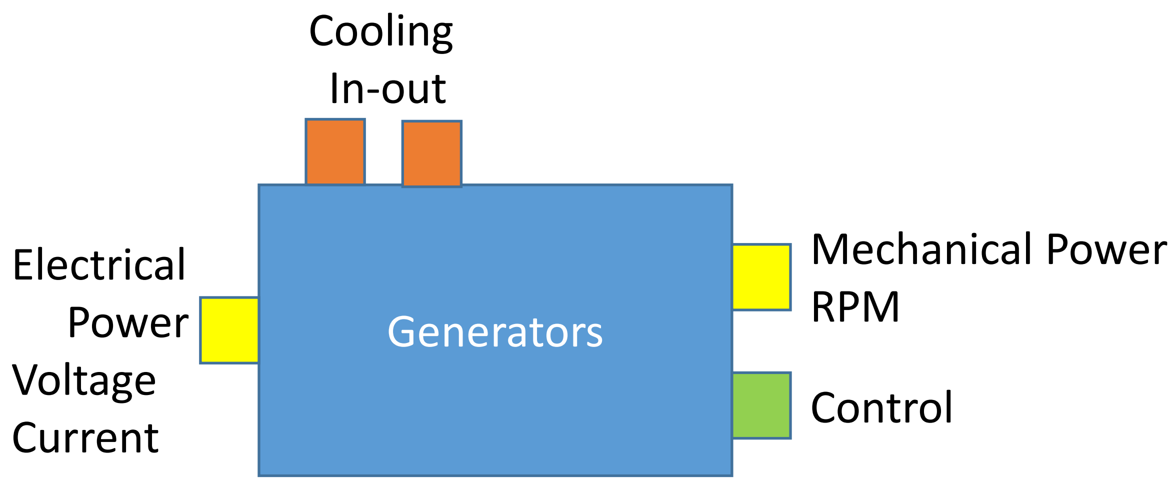
Mechanical Power depends on ship speed (curve)
RPM depends on ship speed (curve)

Common Assumptions

- Mechanical Power is proportional to the cube of ship speed
- RPM is proportional to ship speed
- Mechanical Power includes losses due to shafting and shaft bearings – measured at interface with propulsion motor or reduction gear

Generators

- Primary Interfaces
  - Mechanical Power (Power / RPM)
  - Electrical Interface (Power / Volts / Current) (complex)
- Secondary Interfaces (generally do not model)
  - Cooling (temperature, kg/s)
- Control Interface
  - Depends on system implementation
    - Voltage magnitude and angle (swing)
    - Real and Reactive Power (non-swing)
- Primary Properties
  - Rated Power
  - Rated Voltage
  - Efficiency Curve
  - Rated Speed / Frequency
  - Online



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

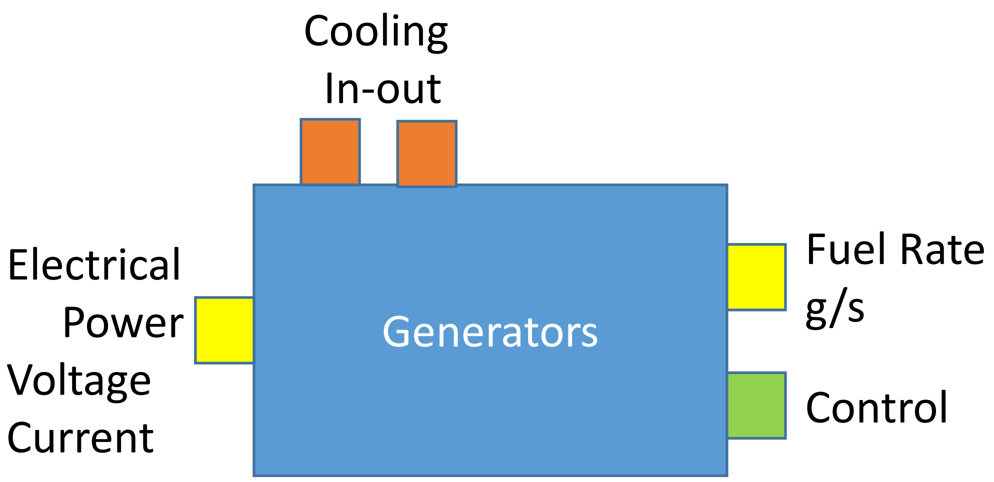
For multi-megawatt generators operating at rated voltages between 1 kV and 15 kV

$$x = \begin{vmatrix} \left(\frac{S_{rated}\, R_{loss}}{3{V_{out}}^2}\right) \\ \left(\frac{P_{noLoadLoss}}{S_{rated}}\right) \end{vmatrix} = \begin{vmatrix} 0.0287 \\ 0.013 \end{vmatrix} \; to \; \begin{vmatrix} 0.0104 \\ 0.010 \end{vmatrix}$$

Mechanical Power is Electrical Real Power + losses
RPM depends on rated frequency
Voltage for swing generator set to operating voltage
Apparent power set for non-swing generators

Generator Sets

- Primary Interfaces
  - Fluid Interface (mass flow rate)
  - Electrical Interface (Power / Volts / Current) (complex)
- Secondary Interfaces (generally do not model)
  - Cooling (temperature, kg/s)
- Control Interface
  - Depends on system implementation
    - Voltage magnitude and angle (swing)
    - Real and Reactive Power (non-swing)
- Primary Properties
  - Rated Power
  - Rated Voltage
  - Efficiency Curve
  - Rated Speed / Frequency
  - Online

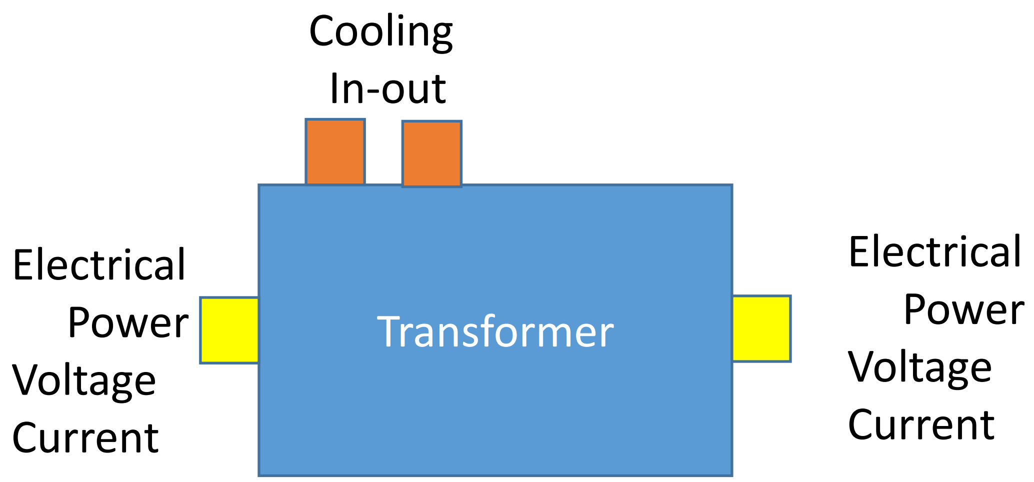


Fuel Rate depends on Electrical Real Power + SFC Curve
Voltage for swing generator set to operating voltage
Apparent power set for non-swing generators

Efficiency used to determine
Cooling load

Transformers

- Primary Interfaces
  - Electrical Interfaces (Power / Volts / Current) (complex)
    - Primary (ac only)
    - Secondary (ac only)
- Secondary Interfaces (generally do not model)
  - Cooling (temperature, kg/s)
- Control Interface
  - none
- Primary Properties
  - Rated Power
  - Rated Voltage
  - Efficiency Curve

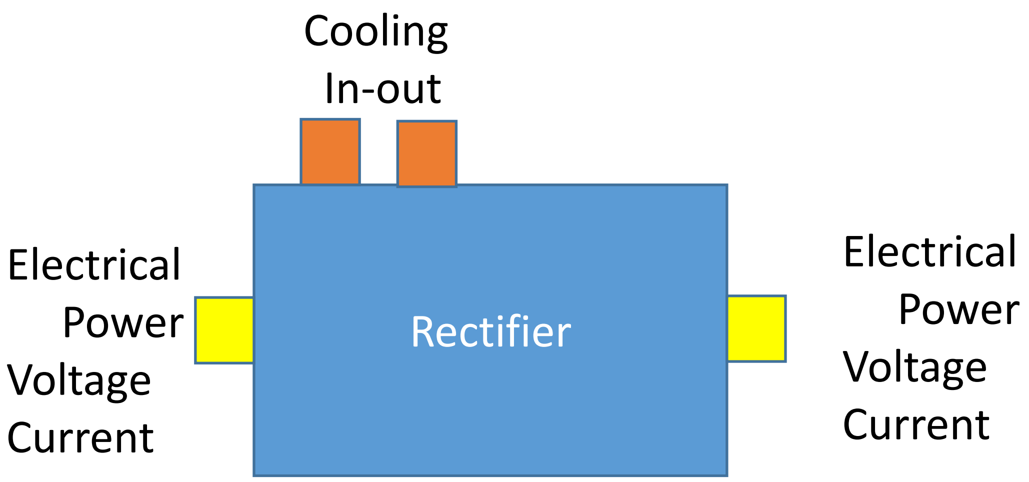


Real Power on port with positive real power is equal
To losses minus real power on port with negative real power
Ratio of voltages on both ports equals the ratio of rated voltages

Power Rating (MVA)	Power Rating (MW) at .8 PF	Efficiency Category	No-load losses (kW)	Losses due to Load (kW)	$\left(\frac{S_{rated}R_{loss}}{3V_{out}^2}\right)$	$\left(\frac{P_{noLoadLoss}}{S_{rated}}\right)$
1.0	0.8	B	0.94	9.0	0.009000	0.000940
1.6	1.3	B	1.45	14.0	0.008750	0.000906
2.0	1.6	B	1.80	18.0	0.009000	0.000900
2.5	2.0	B	2.15	22.0	0.008800	0.000860
1.0	0.8	A	0.77	7.6	0.007600	0.000770
1.6	1.3	A	1.20	12.0	0.007500	0.000750
2.0	1.6	A	1.45	15.0	0.007500	0.000725
2.5	2.0	A	1.75	18.5	0.007400	0.000700

Based on ABB 2015

Rectifiers



- Primary Interfaces
  - Electrical Interfaces (Power / Volts / Current) (complex)
    - Primary (ac only)
    - Secondary (dc only)
- Secondary Interfaces (generally do not model)
  - Cooling (temperature, kg/s)
- Control Interface
  - none
- Primary Properties
  - Rated Power
  - Rated Voltage
  - Efficiency Curve
  - online
  - DC output voltage

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

$$0.005 \leq \frac{P_{noLoadLoss}}{P_{rated}} \leq 0.010$$

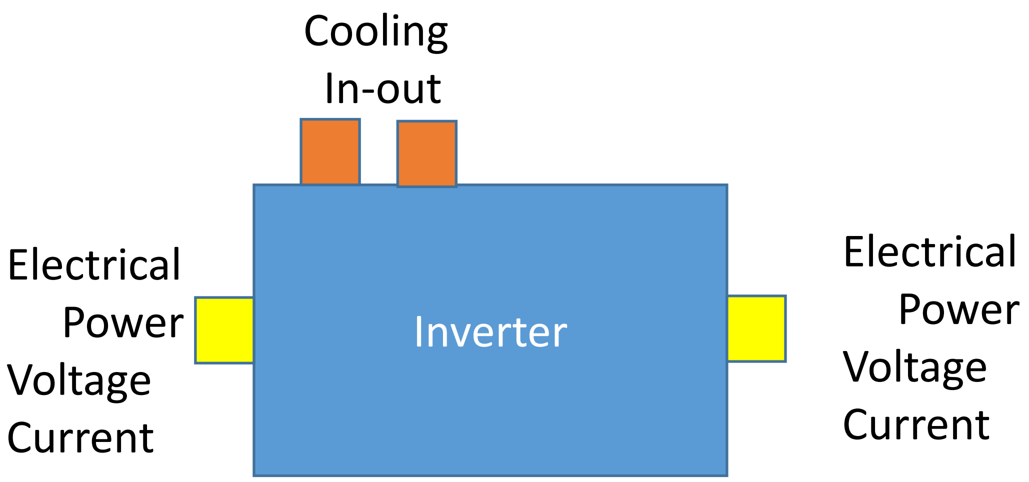
$$0.0051 \leq \frac{P_{rated}\ R_{loss}}{V_{out}{}^{2}} \leq 0.0317$$

Assumes active Rectifier. For passive rectifier, DC voltage a function of AC voltage and efficiency is about 0.999

Bi-directional: Real Power on port with positive real power is equal To losses minus real power on port with negative real power
Unidirectional: Real power on ac port is equal to real power provided on dc port plus losses.

Inverters

- Primary Interfaces
  - Electrical Interfaces (Power / Volts / Current) (complex)
    - Primary (dc only)
    - Secondary (ac only)
- Secondary Interfaces (generally do not model)
  - Cooling (temperature, kg/s)
- Control Interface
  - none
- Primary Properties
  - Rated Power
  - Rated Voltage
  - Efficiency Curve
  - online
  - Swing: ac output voltage mag and angle
  - non-swing: real and reactive power



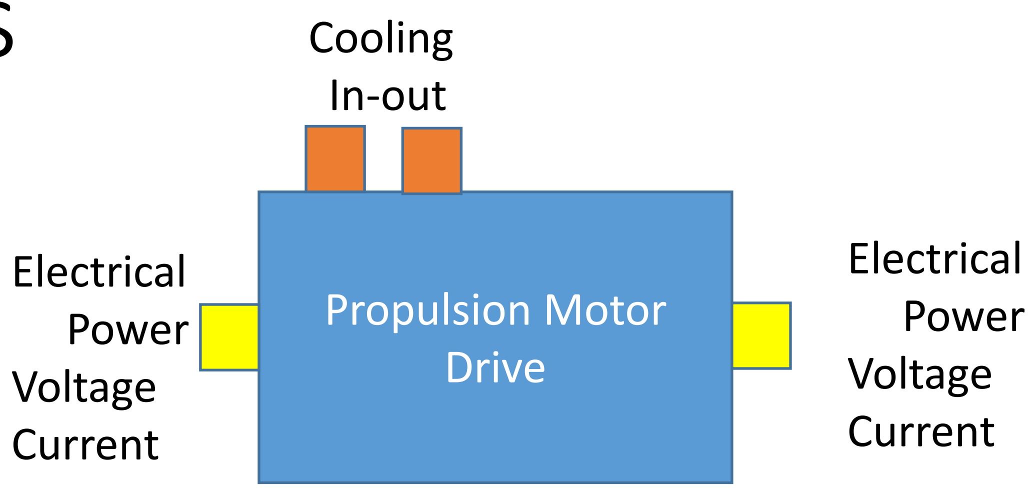
$$\eta = \frac{\frac{P_{out}}{S_{rated}}}{\frac{S_{rated}R_{loss}}{3{V_{out}}^2}\left(\frac{1}{(PF)}\right)^2\left(\frac{P_{out}}{S_{rated}}\right)^2 + \frac{P_{out}}{S_{rated}} + \frac{P_{noLoadLoss}}{S_{rated}}}$$

$$0.005 \leq \frac{P_{noLoadLoss}}{S_{rated}} \leq 0.010$$

$$0.0051 \leq \frac{S_{rated}\ R_{loss}}{3{V_{out}}^2} \leq 0.0317$$

Bi-directional: Real Power on port with positive real power is equal To losses minus real power on port with negative real power
Unidirectional: Real power on dc port is equal to real power provided on ac port plus losses.

Propulsion Motor Drives

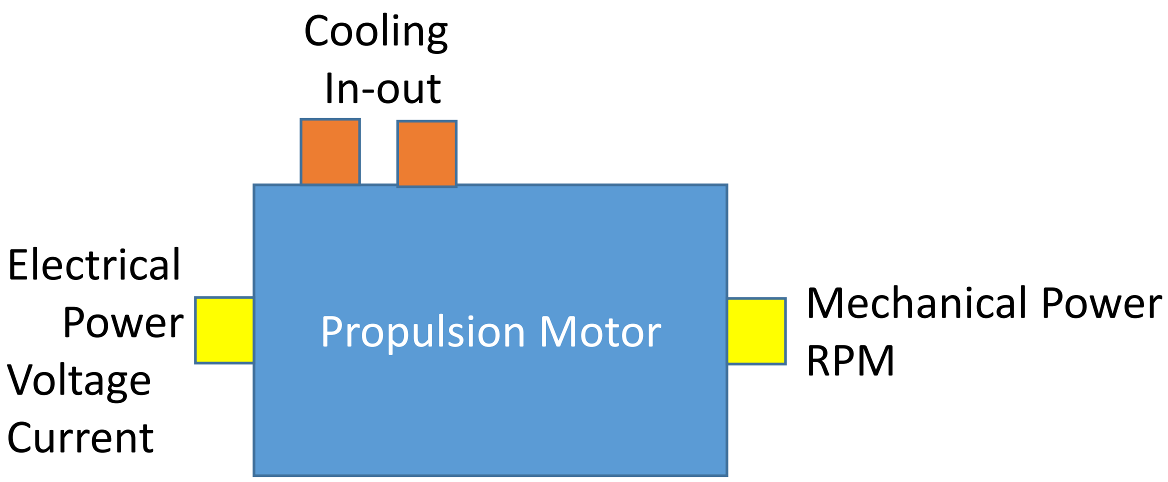


- Primary Interfaces
  - Electrical Interfaces (Power / Volts / Current) (complex)
    - Primary (ac only)
    - Secondary (ac only)
- Secondary Interfaces (generally do not model)
  - Cooling (temperature, kg/s)
- Control Interface
  - none
- Primary Properties
  - Rated Power
  - Rated Voltage
  - Efficiency Curve
  - Output voltage

- Frequency of secondary is variable, but typically not modelled
- Efficiency a product of efficiencies of different possible stages
  - Input transformer (if not modeled separately)
  - Front end rectifier
  - Inverter
- Must account for rating differences of stages
- Real Power on primary is equal to losses plus real power provided on secondary

Propulsion Motors

- Primary Interfaces
  - Mechanical Power (Power / RPM)
  - Electrical Interface (Power / Volts / Current) (complex) (ac)
- Secondary Interfaces (generally do not model)
  - Cooling (temperature, kg/s)
- Control Interface
  - none
- Primary Properties
  - Rated Power
  - Rated Voltage
  - Efficiency Curve
  - Rated Speed / Frequency
  - Online
  - Power Factor

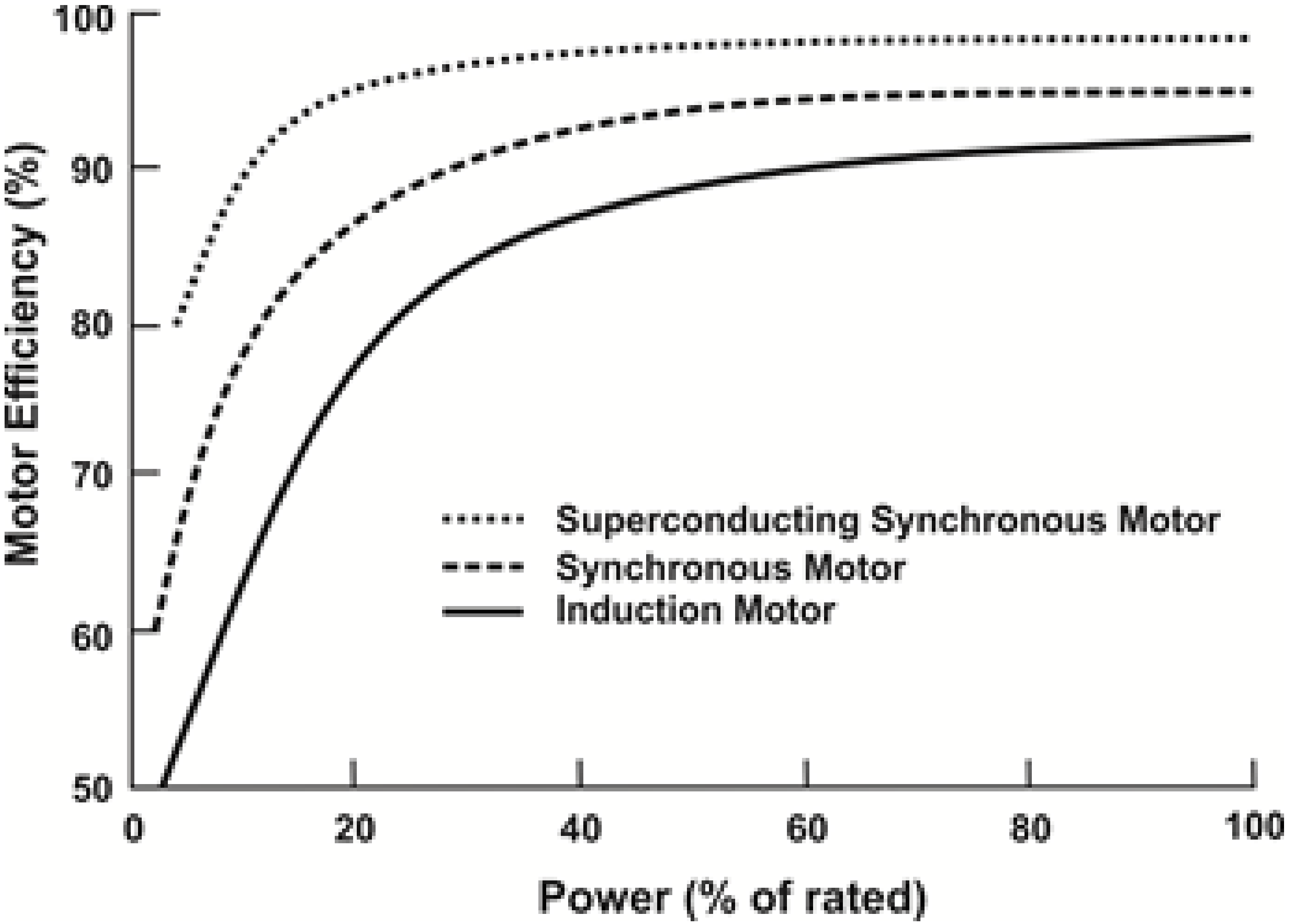


Electrical Real Power is Mechanical Power + losses

Electrical Reactive Power determined from Real power and power factor

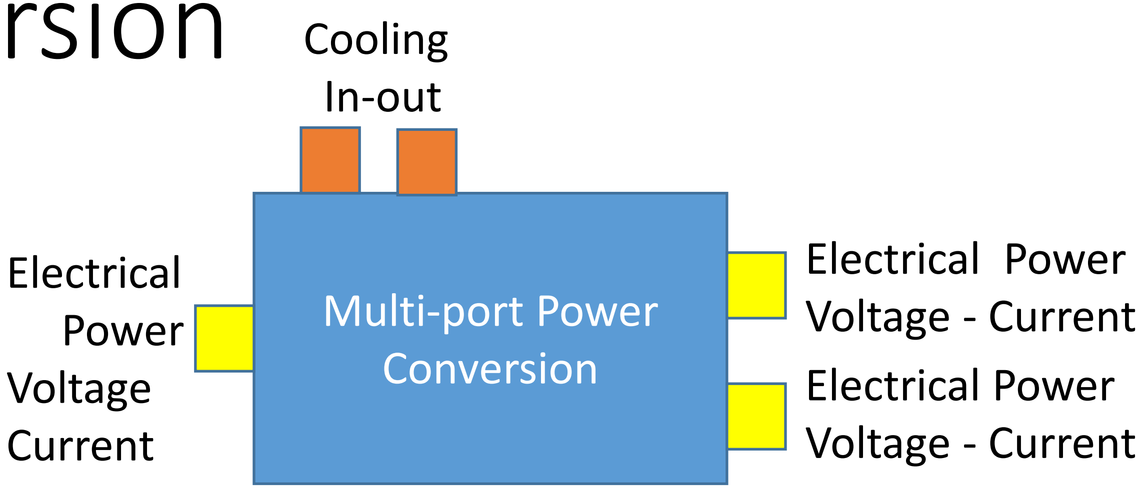
Frequency and RPM related by Rated frequency / Speed

Propulsion Motor Efficiency



(adapted from Patel 2012)

Multi-port Power Conversion



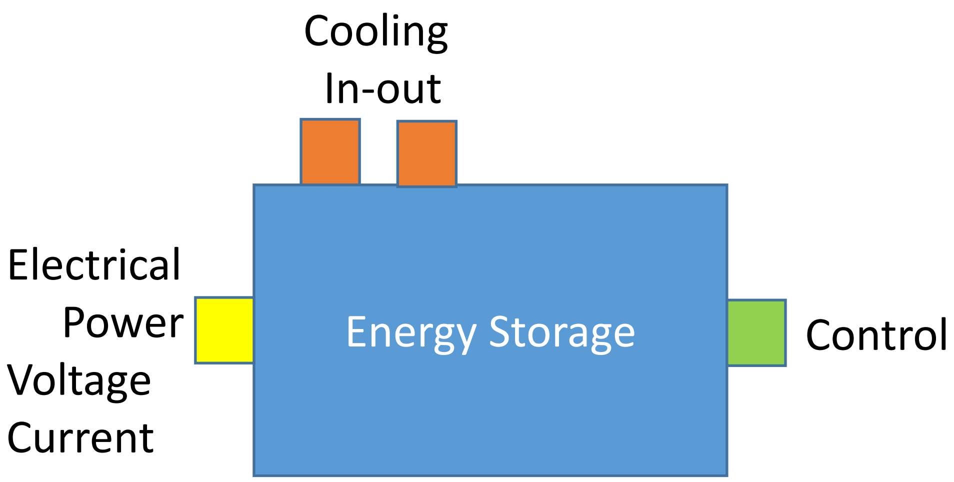
- Primary Interfaces
  - Electrical Interfaces (Power / Volts / Current) (complex)
    - Can be ac or dc at any interface
- Secondary Interfaces (generally do not model)
  - Cooling (temperature, kg/s)
- Control Interface
  - none
- Primary Properties
  - Rated Power
  - DC outputs - Voltage
  - AC outputs – Swing – Voltage mag and angle
  - AC outputs – non-swing – Real and Reactive power
  - Efficiency Curves for each interface

Real Power on port with positive real power is equal to losses minus share of real power on ports with negative real power

Losses calculated based on efficiency for each port – assumes two stage power conversion

Energy Storage

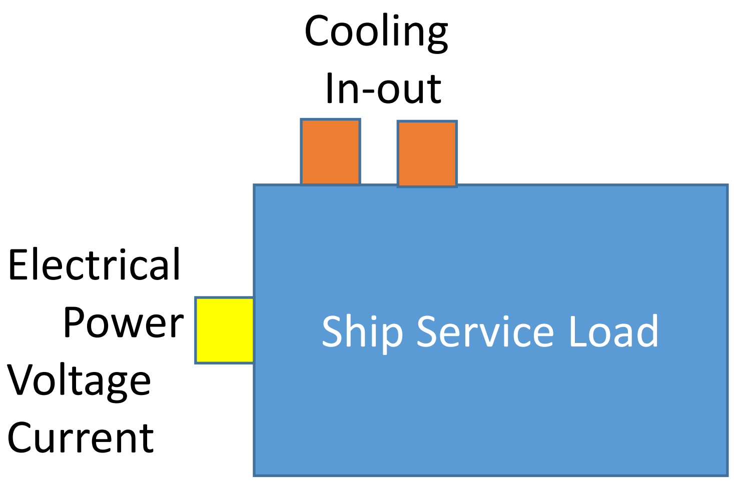
- Primary Interfaces
  - Electrical Interfaces (Power / Volts / Current) (complex)
    - Primary (ac only)
    - Secondary (ac only)
- Secondary Interfaces (generally do not model)
  - Cooling (temperature, kg/s)
- Control Interface
  - Charging or Discharging
  - State of Charge (SOC) (actually a state)
- Primary Properties
  - Rated Power
  - Rated Voltage
  - Charging: Rate of charge as function of SOC
  - Discharging: Swing – voltage
  - Discharging: non-swing - power



If charging, power is determined by SOC curve and SOC
If discharging, depends on if swing (voltage vs power)

Ship Service Loads

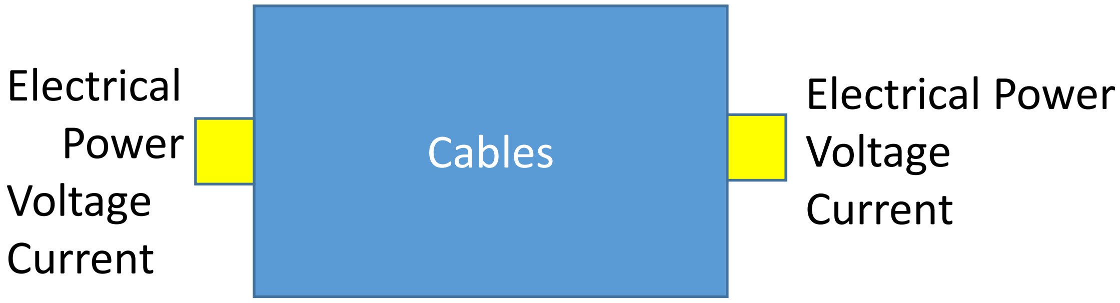
- Primary Interfaces
  - Electrical Interfaces (Power / Volts / Current)
    - Ac or dc
- Secondary Interfaces (generally do not model)
  - Cooling (temperature, kg/s)
- Control Interface
  - none
- Primary Properties
  - Real Power
  - Reactive Power (ac only)



Ship Service Loads determined from Electric Plant Load Analysis (EPLA)

Cables

- The need to model cables depends on power solver details.
  - Usually losses in cables are very small.
  - System convergence may depend on each a.c. source having a cable.
- Primary Interfaces
  - Electrical Interfaces (on at each end)
- Primary Properties
  - Resistance per unit length
  - Inductance per unit length
  - Length
  - (Number of cables in bundle)
  - (ampacity)



$$V_1 - V_2 = (R + L\omega\hat{j})I_1$$

$$I_1 + I_2 = 0$$

$$S_1 = \sqrt{3}V_1 {I_1}^* \quad S_2 = \sqrt{3}V_2 {I_2}^*$$

Voltage, Current, Power at interfaces depend on
Resistance per unit length
Inductance per unit length (ac only)
Length

Electrical Power System Concept of Operations

- Provides guidance to determine
  - Which generator sets are online
  - Which power conversion equipment are online
  - Configuration of switchgear
  - Operating modes of power system components
- Different operating conditions may have different guidance

		Generator Set 1A	Generator Set 1B	Generator Set 2A	Generator Set 2B
	Rating (MW)	20	5	20	5
Total Load	up to 9.5 MW	offline	share	offline	share
	9.5 to 23.75 MW	share	offline	offline	share
	23.75 to 28.5 MW	share	share	offline	share
	28.5 to 38 MW	share	offline	share	offline
	38 to 42.75 MW	share	share	share	offline
	42.75 to 50 MW	share	share	share	share

Propulsion System Concept of Operations

- Provides guidance to determine
  - Which propulsion motors / prime movers are online
  - Which propulsion motor drives are online
  - Power sharing among different shafts
  - Power sharing among motors / drives on same shaft
- Different operating conditions may have different guidance

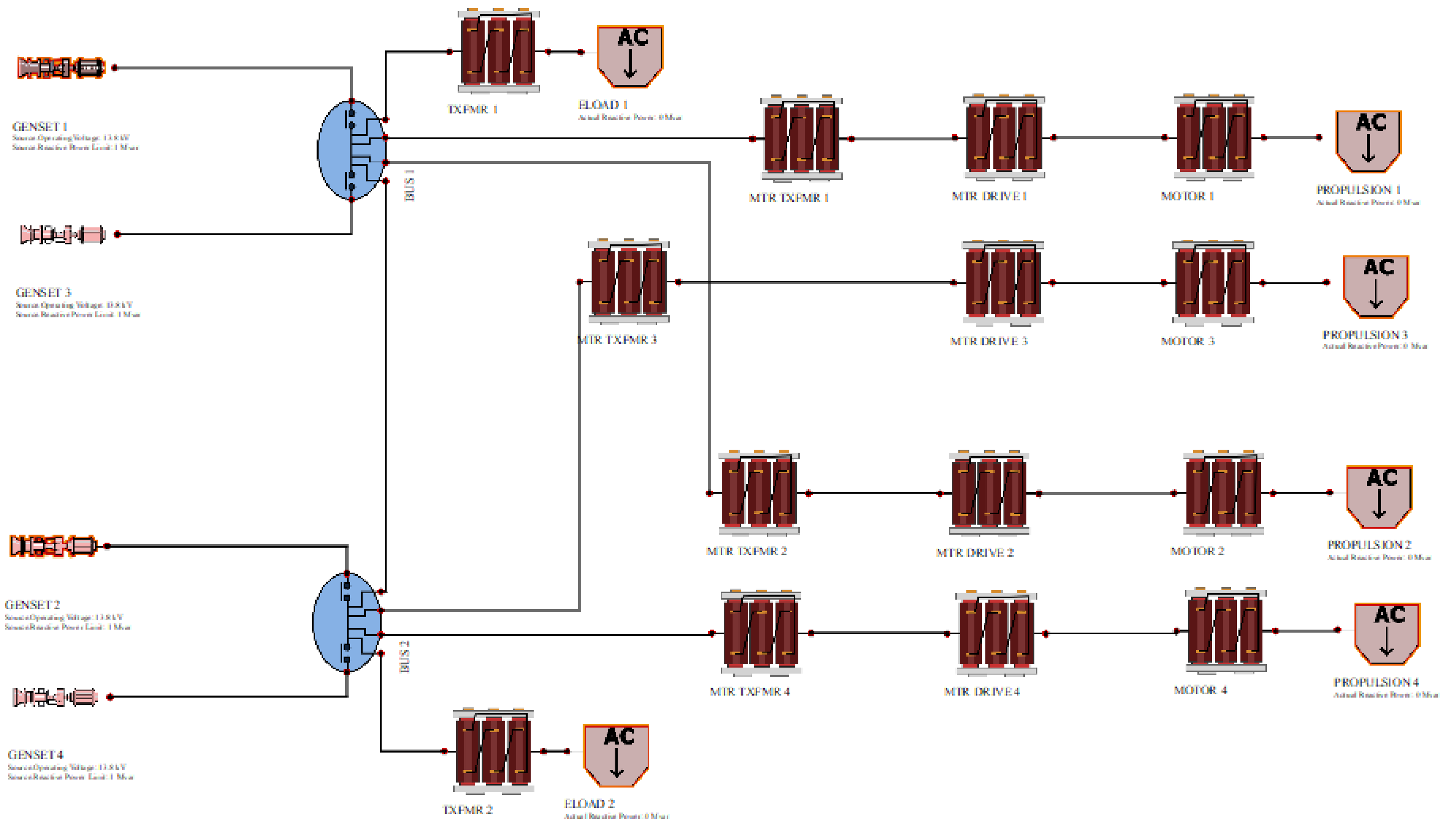
	Propulsion Motor 1	Propulsion Motor 2	Propulsion Motor 3	Propulsion Motor 4
Rating (MW)	15	15	15	15
0 < Total Propulsion <= 30 MW	1/2 Power	offline	offline	1/2 Power
30 < Total Propulsion <= 60 MW	1/4 Power	1/4 Power	1/4 Power	1/4 Power

	Propulsion Motor 1	Propulsion Motor 2	Propulsion Motor 3	Propulsion Motor 4
Rating (MW)	15	15	15	15
Genset 3 and 4 online, Genset 1 and 2 offline. Propulsion less than 20 MW	1/2 power	offline	offline	1/2 power
Genset 1 online Genset 2 offline Propulsion <= 30 MW	1/2 power	1/2 power	offline	offline
Genset 1 and 2 online, Propulsion <= 30 MW	1/2 power	offline	offline	1/2 power
30 MW < Propulsion < 60 MW	1/4 power	1/4 power	1/4 power	1/4 power

Modeling Systems

- System model depends on modeling tool
  - May require cleverness to model all the required components.
  - Spreadsheet tools are not unusual

Basic S3D Model using minimal component types



Run Matrix

Run	Temp	Speed (knots)	Generator Set 1	Generator Set 2	Generator Set 3	Generator Set 4	Motor 1 (MW)	Motor 2 (MW)	Motor 3 (MW)	Motor 4 (MW)	Load 1 (MW)	Load 2 (MW)	Note
1	10	17	offline	offline	swing	swing	5.46	offline	offline	5.46	2.1	2.4	Economic Transit
2	50	17	offline	offline	swing	swing	5.46	offline	offline	5.46	1.8	2.2	Economic Transit
3	100	17	offline	offline	swing	swing	5.46	offline	offline	5.46	2.0	2.3	Economic Transit
4	10	27	23.75 MW	23.75 MW	swing	swing	10.94	10.94	10.94	10.94	2.1	2.4	Surge to theater
5	50	27	23.75 MW	23.75 MW	swing	swing	10.94	10.94	10.94	10.94	1.8	2.2	Surge to theater
6	100	27	23.75 MW	23.75 MW	swing	swing	10.94	10.94	10.94	10.94	2.0	2.3	Surge to theater
7	10	5	offline	offline	swing	swing	0.14	offline	offline	0.14	3.6	3.9	Operational Presence
8	50	5	offline	offline	swing	swing	0.14	offline	offline	0.14	3.3	3.7	Operational Presence
9	100	5	offline	offline	swing	swing	0.14	offline	offline	0.14	3.5	3.8	Operational Presence
10	10	10	offline	offline	swing	swing	1.11	offline	offline	1.11	3.6	3.9	Operational Presence
11	50	10	offline	offline	swing	swing	1.11	offline	offline	1.11	3.3	3.7	Operational Presence
12	100	10	offline	offline	swing	swing	1.11	offline	offline	1.11	3.5	3.8	Operational Presence
13	10	15	offline	offline	swing	swing	3.75	offline	offline	3.75	3.6	3.9	Operational Presence
14	50	15	offline	offline	swing	swing	3.75	offline	offline	3.75	3.3	3.7	Operational Presence
15	100	15	offline	offline	swing	swing	3.75	offline	offline	3.75	3.5	3.8	Operational Presence
16	10	20	swing	offline	offline	swing	8.89	8.89	offline	offline	3.6	3.9	Operational Presence
17	50	20	swing	offline	offline	swing	8.89	8.89	offline	offline	3.3	3.7	Operational Presence
18	100	20	swing	offline	offline	swing	8.89	8.89	offline	offline	3.5	3.8	Operational Presence
19	10	25	swing	swing	offline	offline	8.68	8.68	8.68	8.68	3.6	3.9	Operational Presence
20	50	25	swing	swing	offline	offline	8.68	8.68	8.68	8.68	3.3	3.7	Operational Presence
21	100	25	swing	swing	offline	offline	8.68	8.68	8.68	8.68	3.5	3.8	Operational Presence

Post Processing - Endurance Fuel

Run	Temp	Speed (knots)	Fuel Rate (kg/s)	Ambient Condition Profile	Operational Profile	Operational Profile Fuel Rate (kg/s)	Required Range (NM)	Required Time (hrs)	Burnable Fuel (t)
1	10	17	0.972	0.25					
2	50	17	0.944	0.50					
3	100	17	0.961	0.25					
ambient cond. profile		17	0.955		N/A		5000	294.1	1062
4	10	27	3.84	0.25					
5	50	27	3.81	0.50					
6	100	27	3.83	0.25					
ambient cond. profile		27	3.823		N/A		2000	74.1	1070
7	10	5	0.54	0.25					
8	50	5	0.513	0.50					
9	100	5	0.529	0.25					
ambient cond. profile		5	0.524		0.25	0.131			
10	10	10	0.648	0.25					
11	50	10	0.62	0.50					
12	100	10	0.637	0.25					
ambient cond. profile		10	0.631		0.35	0.221			
13	10	15	0.942	0.25					
14	50	15	0.914	0.50					
15	100	15	0.931	0.25					
ambient cond. profile		15	0.925		0.25	0.231			
16	10	20	1.97	0.25					
17	50	20	1.94	0.50					
18	100	20	1.95	0.25					
ambient cond. profile		20	1.950		0.10	0.195			
19	10	25	3.44	0.25					
20	50	25	3.41	0.50					
21	100	25	3.43	0.25					
ambient cond. profile		25	3.423		0.05	0.171			
			Operational Presence Fuel Rate (kg/s) =			0.949		300	1077

Economical Transit Burnable Fuel Load (t)	1062
Surge to Theater Burnable Fuel Load (t)	1070
Operational Presence Burnable Fuel Load (t)	1077
Design Burnable Fuel Load (t)	1077
Tailpipe Allowance	0.95
Endurance Fuel Load (t)	1133
density of Fuel (kg/l) = (t/m3)	0.84
Fuel Tank Volume Requirement (m3)	1445

Post Processing - Annual Fuel

Fuel rate for ship state (see endurance fuel calcs)

	Inport - shore (shore power)	Underway Economical Transit	Underway Surge to Theater	Underway Mission
Fuel Rate (kg/hr)	0	3435	13707	3420

Ship State Participation Table (input to process)

operational mode / ship state	Inport - shore (shore power)	Underway Economical Transit	Underway Surge to Theater	Underway Mission	Fraction of Time in operational mode
Maintenance Mode	0.9	0.05	0	0.05	0.1
Operation Mode A	0.4	0.2	0.1	0.3	0.4
Operation Mode B	0.1	0.2	0.2	0.5	0.5

Annual Fuel usage

operational mode / ship state	Inport - shore (shore-to-ship power) (Annual Fuel usage (t))	Underway - Economical Transit (Annual Fuel usage (t))	Underway - Surge to Theater (Annual Fuel Usage (t))	Underway - Mission (Annual Fuel Usage (t))	Total Annual Fuel Usage (t)
Maintenance Mode	0	151	0	150	300
Operation Mode A	0	2409	4806	3598	10813
Operation Mode B	0	3011	12016	7495	22522
			Annual Total (t) =		33636

Annual Fuel Usage (t)	33,636
Density of Fuel (t/m3)	0.84
Annual Fuel Usage (m3)	40,043
42 gal barrel (m3)	0.1590
Annual Fuel Useage (barrels)	251,861

Summary

- Modeling ship systems for endurance fuel and annual fuel calculations is straightforward
  - Not necessarily easy.

- The Devil is in the detail

220713-N-FT160-1020
PACIFIC OCEAN (July 13, 2022) The Indonesian navy frigate KRI I Gusti Ngurah Rai (332) conducts an underway replenishment with the U.S. Navy's Military Sealift Command fleet replenishment oiler USNS Henry J. Kaiser (T-AO 187) during the at-sea phase of Rim of the Pacific (RIMPAC) 2022

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