Electric Ship Power and Energy System Architectures

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Agenda

- Naval Power (and Energy Systems
- Existing Ships
- MVAC Architectures
- MVDC Architectures

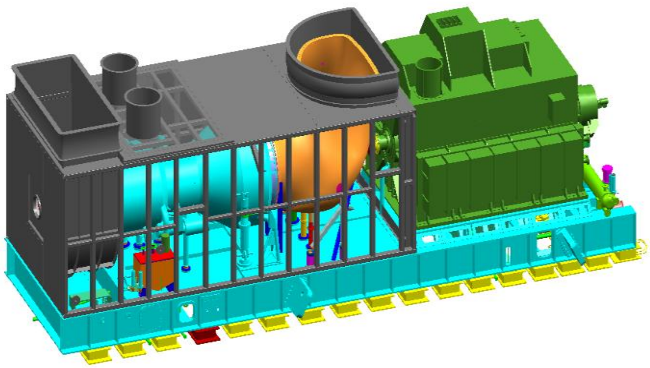
Dec 8, 2016: DDG 1000 and LCS 2
(US Navy Photo by Ace Rheaume)

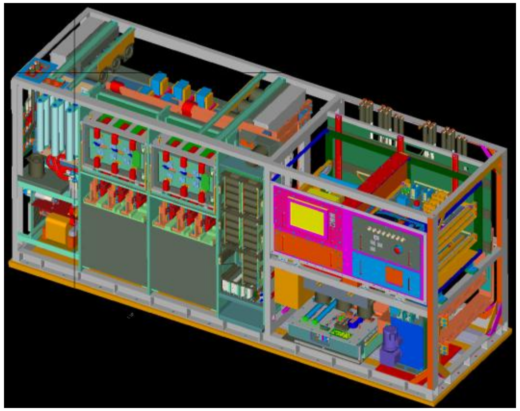
MVAC Architectures

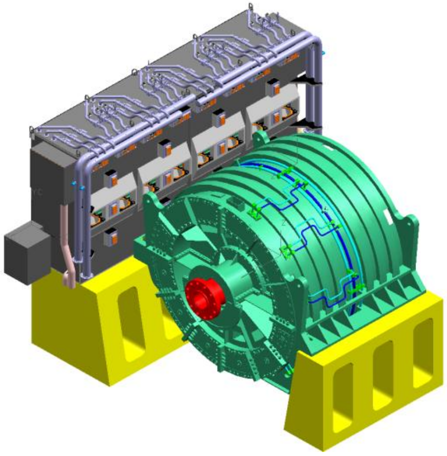
Integrated Power System (IPS)

IPS consists of an architecture and a set of modules which together provide the basis for designing, procuring, and supporting marine power systems applicable over a broad range of ship types:

- Power Generation Module (PGM)
- Propulsion Motor Module (PMM)
- Power Distribution Module (PDM)
- Power Conversion Module (PCM)
- Power Control (PCON)
- Energy Storage Module (ESM)
- Load (PLM)





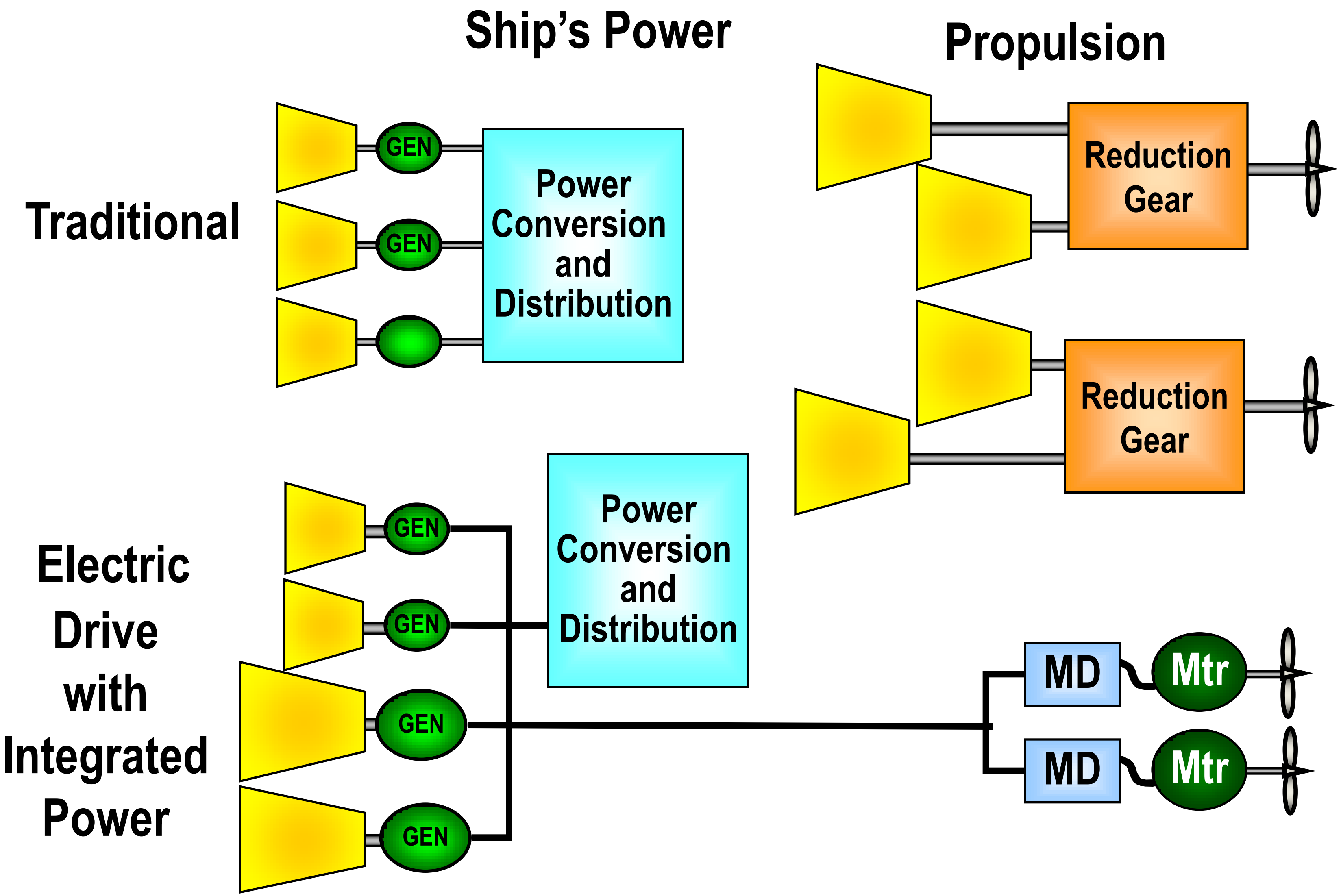


IPS Design Opportunities

- Support High Power Mission Systems
- Reduce Number of Prime Movers
- Improve System Efficiency
- Provide General Arrangements Flexibility
- Improve Ship Producibility
- Support Zonal Survivability
- Improve Quality of Service

161208-N-MB306-079 USS Zumwalt DDG 1000 (US Navy Photo by Zachary Bell)

Reduce Number of Prime Movers



Improve System Efficiency

- A generator, motor drive and motor will generally be less efficient than a reduction gear ….
- But electric drive enables the prime mover and propulsor to be more efficient, as well as reducing drag.

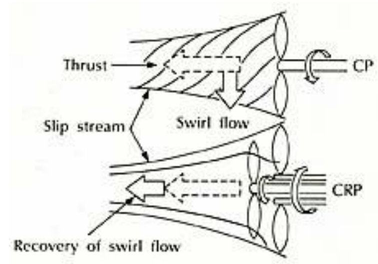
	Mechanical Drive	Electric Drive
Gas Turbine	30%	35%
Reduction Gear	99%	
Generator		96%
Drive		95%
Motor		98%
Propeller	70%	75%
Relative Drag Coefficient	100%	97%
Total	21%	24%
Ratio		116%

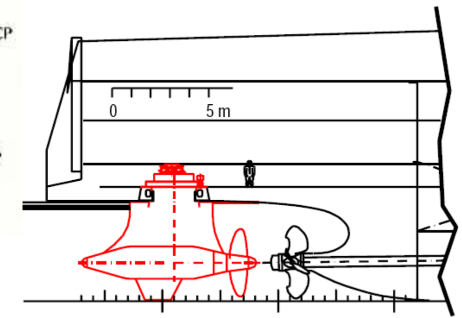
Representative values: not universally true

TRADE TRANSMISSION EFFICIENCY TO REDUCE DRAG
AND IMPROVE PRIME MOVER AND PROPELLER EFFICIENCY

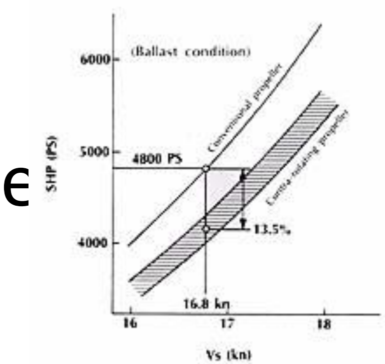
Improve System Efficiency: Contra-Rotating Propellers

- Increased Efficiency
  - Recover Swirl Flow
  - 10 – 15% improvement
- Requires special bearings for inner shaft if using common shaft line
- Recent examples feature Pod for aft propeller





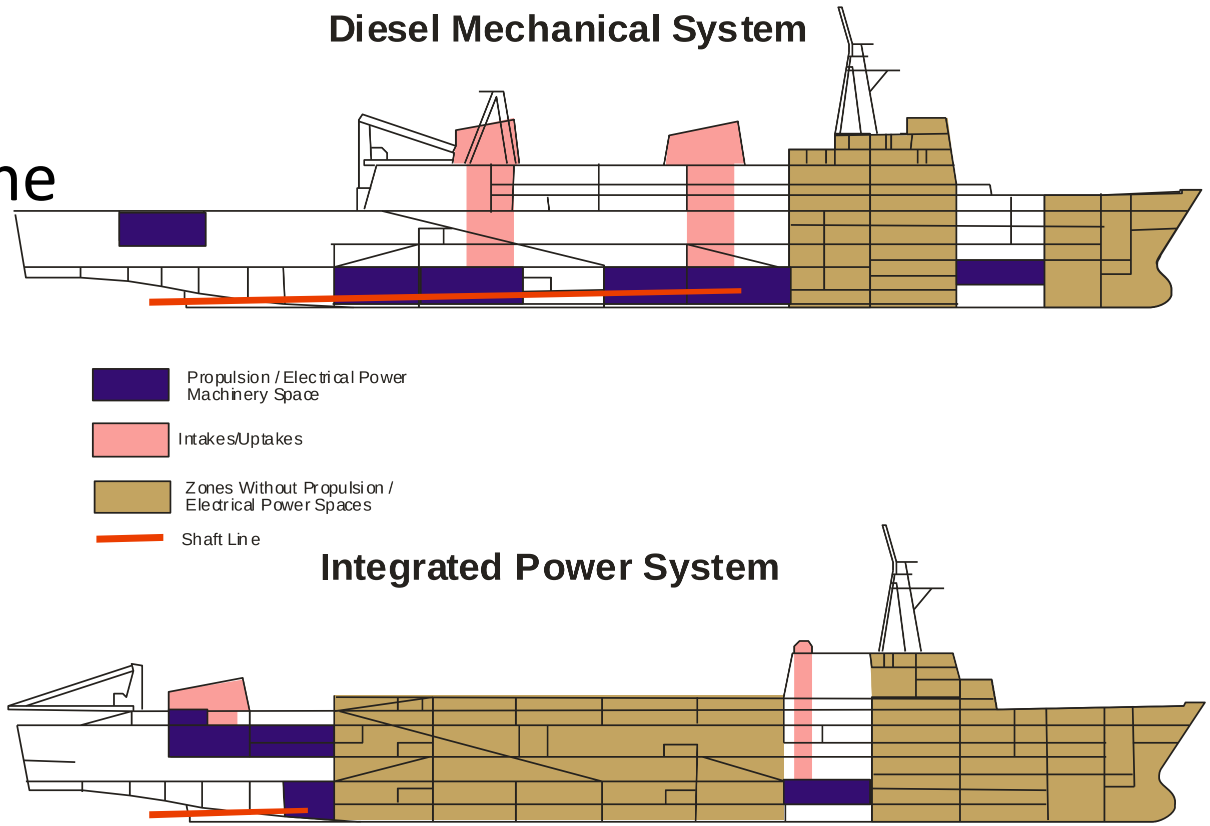
Anders Backlund and Jukka Kuuskoski, "The Contra Rotating Propeller (CRP) Concept with a Podded Drive"



http://www.mhi.co.jp/ship/english/htm/crp01.htm

General Arrangements Flexibility Improve Ship Producibility

- Vertical Stacking of Propulsion Components
- Pods
- Athwart ship Engine Mounting
- Horizontal Engine Foundation
- Engines in Superstructure
- Distributed Propulsion
- Small Engineering Spaces



Topics

- Propulsion
  - Motor Types
  - Options
- Power Generation
- Power Distribution

Propulsion Motors: General Observations

- Propulsion Motors are typically custom designed for the application based on standard "Frame Sizes".
  - Frame size determines rotor diameter.
  - Variables are length and shaft speed.
- The Motor Drive has a large impact on both the Propulsion Motor and the Medium Voltage Distribution System.
  - Harmonics and Power Quality
  - Part Load Efficiency
  - Number of Motor Phases
  - Need for Propulsion Transformer
- Motor Designs have changed significantly in past 15 years to take advantage of new high voltage and current power electronics.
  - Permanent Magnet (PM) and Advanced Induction Motors (AIM) have largely displaced DC and Synchronous Motors for high power applications.
  - Homopolar Motors and Superconducting Motors are still being developed.
- High Efficiency at very Low Power levels challenging
  - 10% shaft power achieves about 35 - 45% speed
  - Consider powering only portions of the motor (Motor Drive integration)
    - Will likely reduce acoustic performance
  - Consider mounting two motors on same shaft (Do not need to be the same rating)
    - Smallest motor must be large enough to achieve "break-away" torque
    - Can help with shaft rake
    - Can reduce torque pulsations on propulsor

Motors: Basic Scaling Law

$$HP \propto D^2 \cdot L \cdot A \cdot B \cdot RPM$$

HP	**Power Rating**
D	**Rotor Diameter**
L	**Rotor Active Length**
A	**Surface Current Density (Cooling Method)**
B	**Rotor Flux Density (Saturation of Magnetic Material)**
RPM	**Shaft Speed**

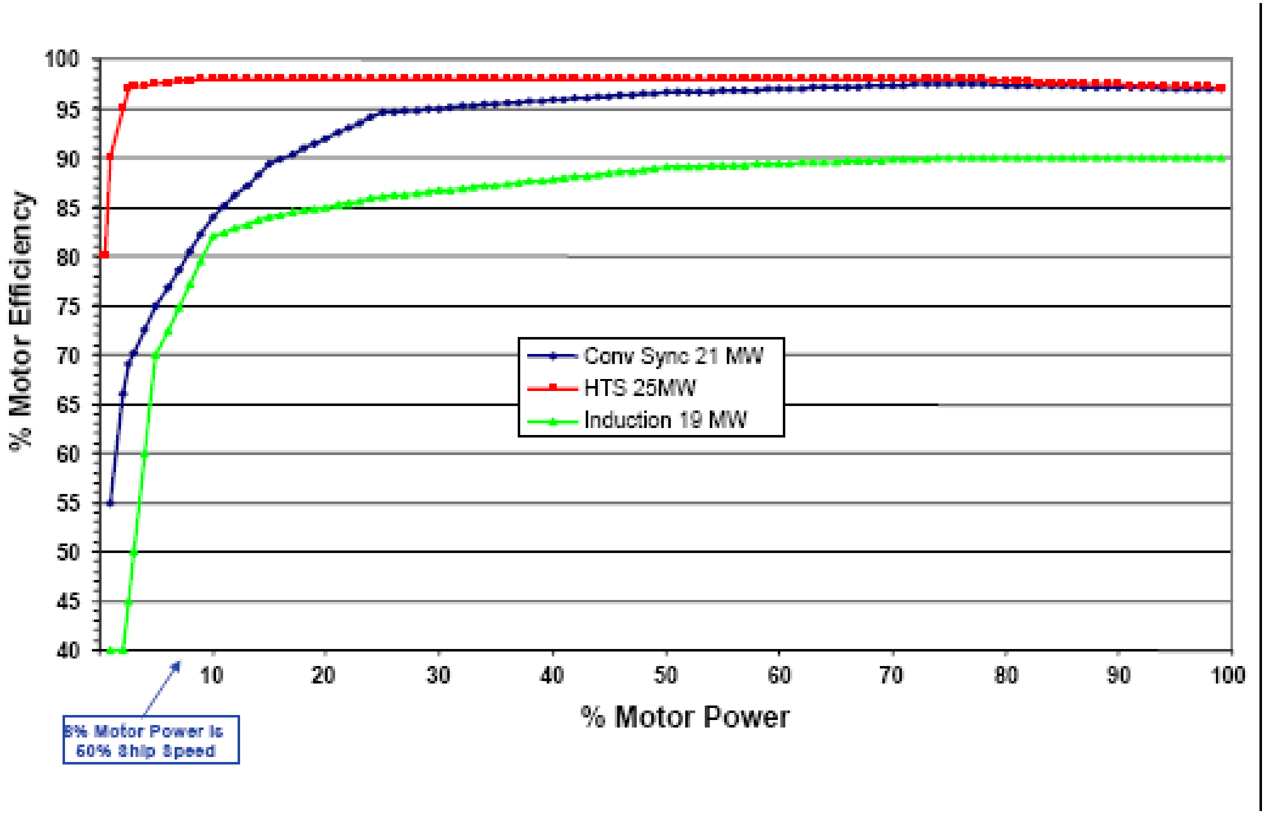
Propulsion Motor Thumb rules

- For a given technology, cost is roughly proportional to Torque.
- As the rated speed of a motor increases, the peak efficiency occurs at a lower diameter.
- Higher rated speeds generally translate into smaller and more efficient motors.
- Maximum Rotor Diameter is limited by shaft rake considerations, manufacturability, and transportability.
- Motor efficiencies at design speed can typically fall in range of 90-98%.
- The efficiency of a conventional motor is relatively flat above about 25-35% rated speed. Below about 25-35% rated speed, the efficiency drops rapidly.

Motor and Drive Efficiency

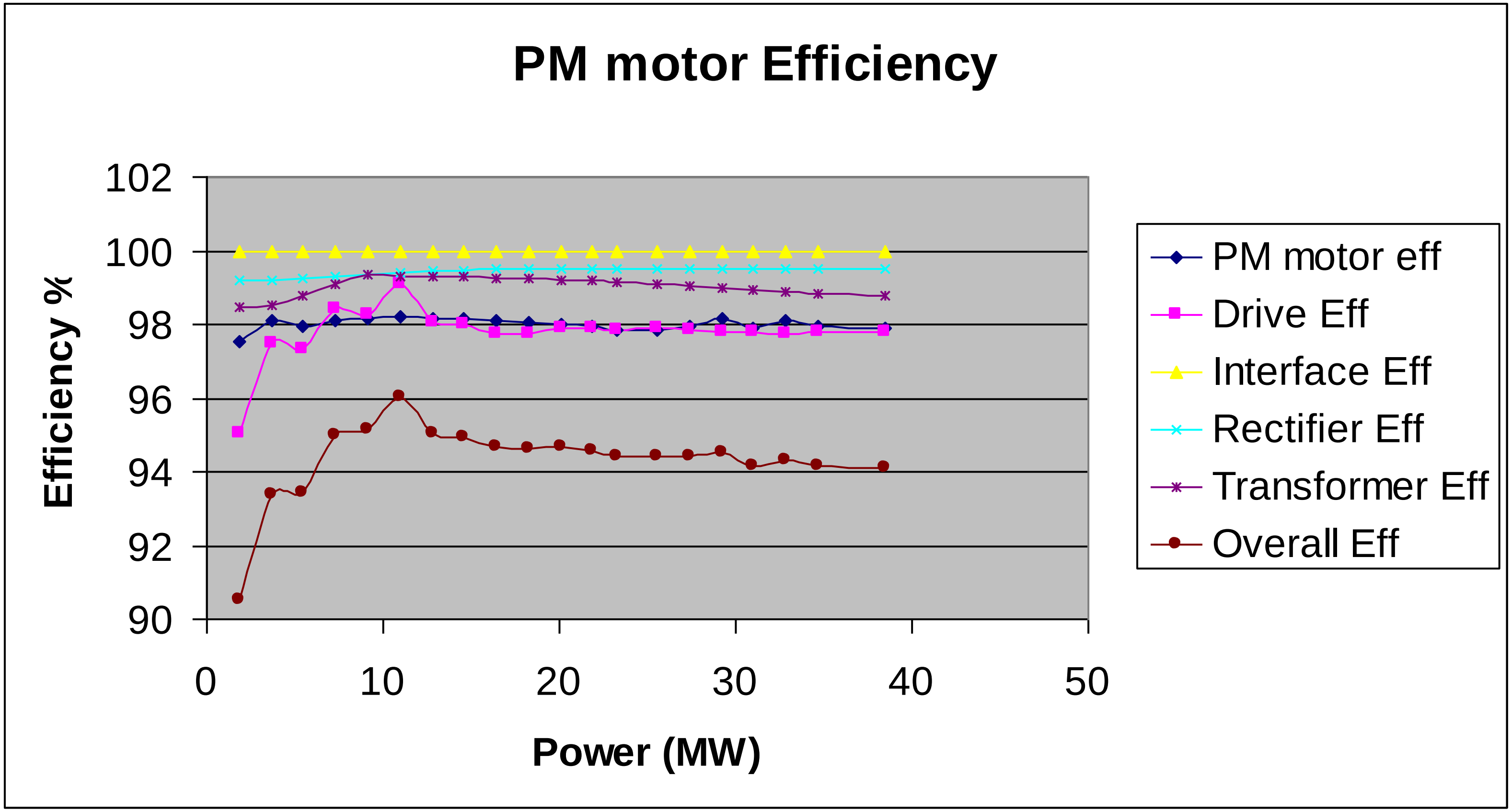
- Motor and Motor Drive efficiencies generally high at high power levels.
- At very low power levels, losses are fairly constant at ~1-4% of full power rating
  - Causes rapid drop off of efficiency below 10% power levels
  - This constant level for losses can be approximated by the power delivered to the propeller when the efficiency is 50%.
- Poor efficiency at low power levels for main propulsion make low power auxiliary propulsion units (at about 10-20% of main propulsion rating) attractive.

Propulsion Motor Efficiencies



http://www.amsuper.com/products/library/HTS_efficiency_advantage.pdf

PM motor efficiency



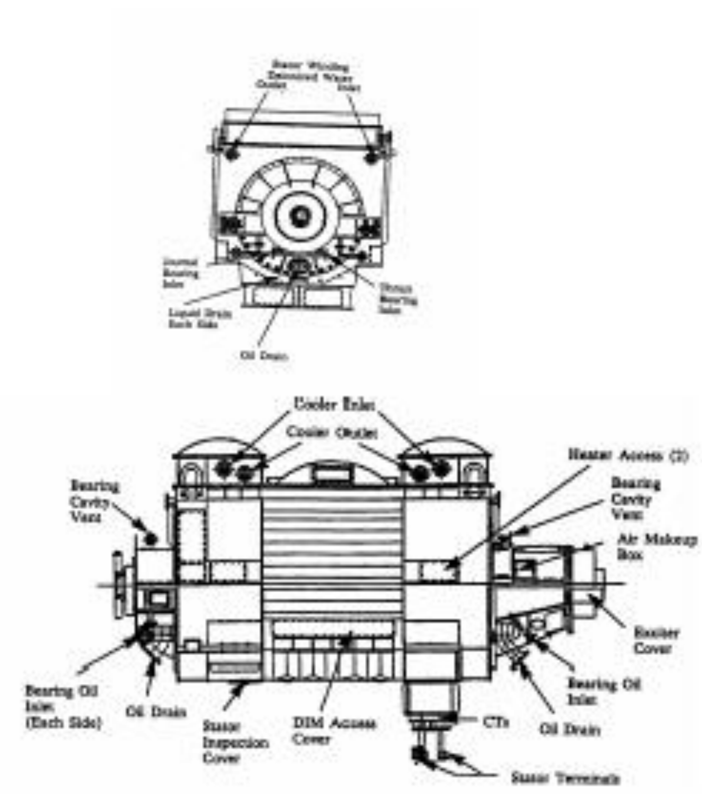
DC Motors

- Pros
  - Proven Technology
  - Simple Drives
- Cons
  - Maintenance Intensive (Brushes)

http://www.tecowestinghouse.com/Products/Custom_Engineered/DC.html

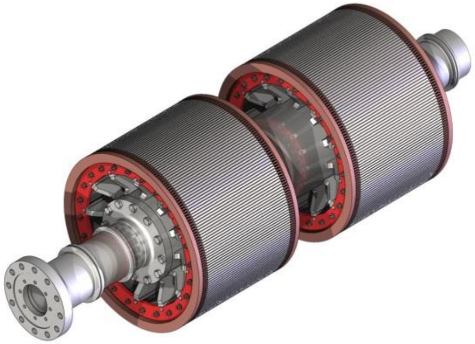
AC Synchronous Motors

- Pros
  - Proven Technology
  - Simple Drive Systems
  - High Efficiencies
- Cons
  - Large and Heavy
  - More expensive and complex than Induction Motors



Advanced Induction Motors

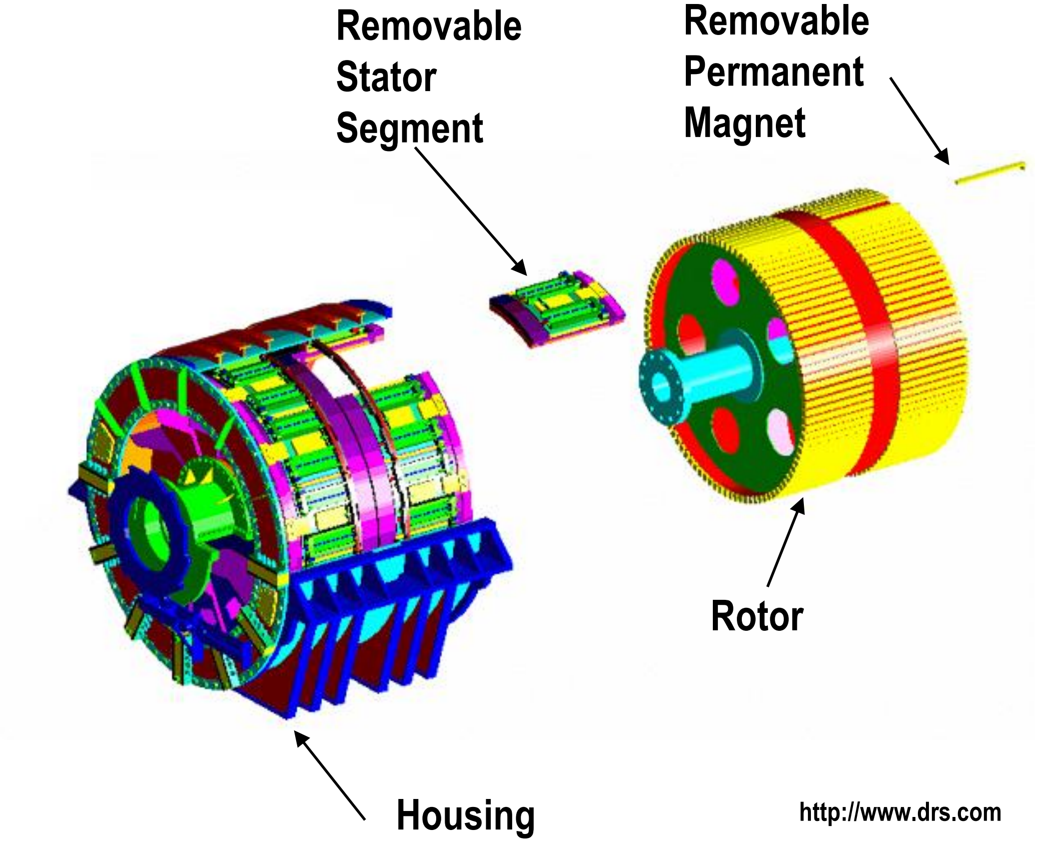
- Pros
  - Proven Technology
  - Modern Drives enable higher efficiencies
- Cons
  - Large and Heavy
  - Efficiencies still not as high as other motor types



http://www.powerconv.alstom.com/home/

Permanent Magnet Motors

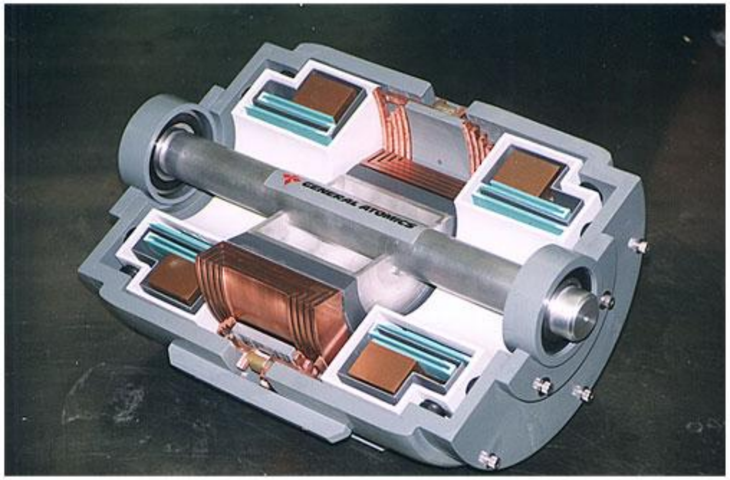
- Pros
  - Low Weight
  - Quieter
  - Better part load efficiency
- Cons
  - Developmental
  - Cost



Homopolar Motors

- Pros
  - True DC Motor
  - Low Noise
  - Low torque pulsations
  - Low Weight
  - Small Size

- Cons
  - Developmental
  - Low Voltage, High Current
  - High-Current Brushes



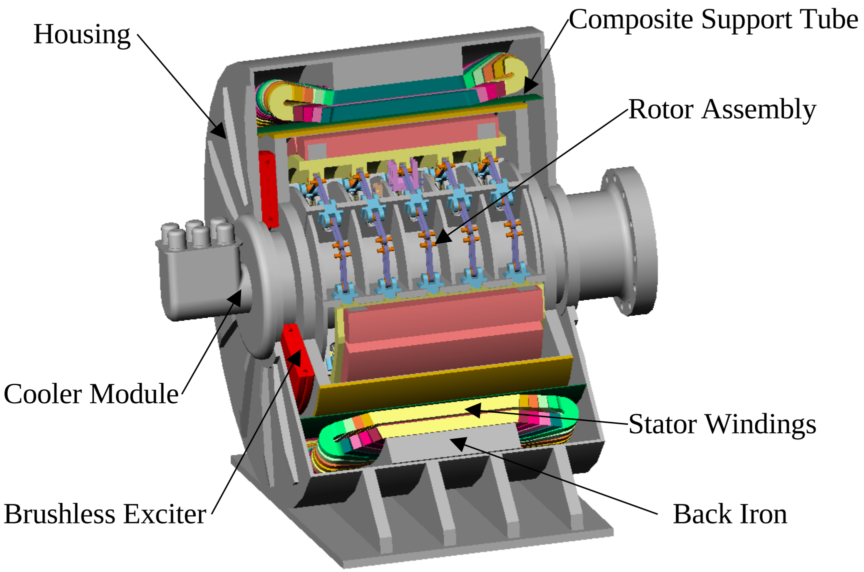
Homopolar motor model in half-section

http://www.ga.com/atg/homo.php

One-quarter scale 5,000 hp motor under construction

Superconducting Motors

- Generally either Synchronous Machines or Homopolar
- Can achieve significantly higher magnetic flux densities
- Promises to significantly reduce the size and weight of Propulsion Motors

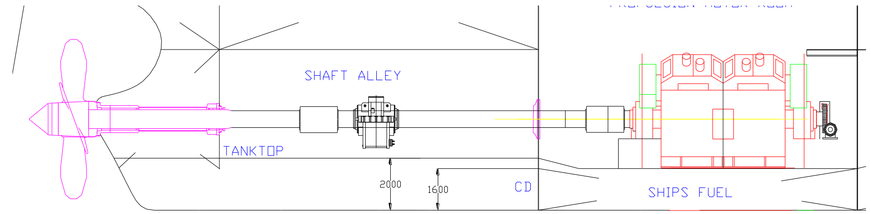


Propulsion Options

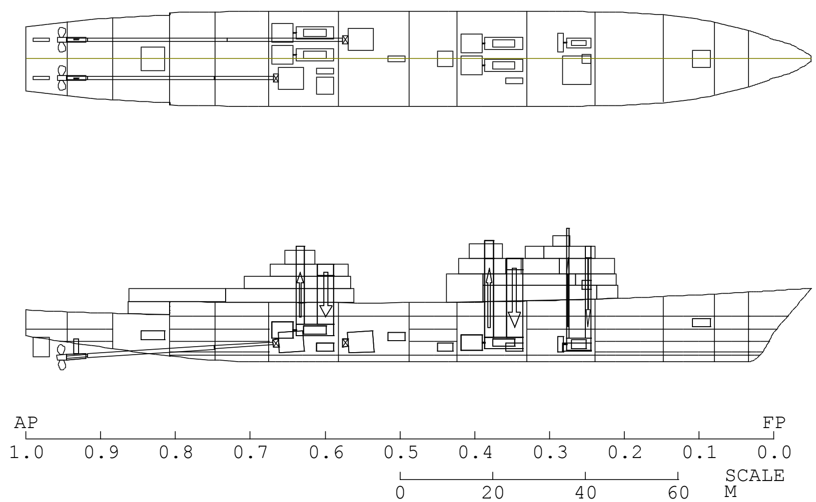
- Conventional
- Pods
- Contra-Rotating
- Waterjets
- Distributed
- Hybrid

Conventional

- Shafts arranged similar to mechanical drive.
- Electric Drive enables
  - Shorter Shafts
  - Eliminate rake on prime movers
    - Simplify foundations
    - Can Lower Center of Gravity of Prime Mover



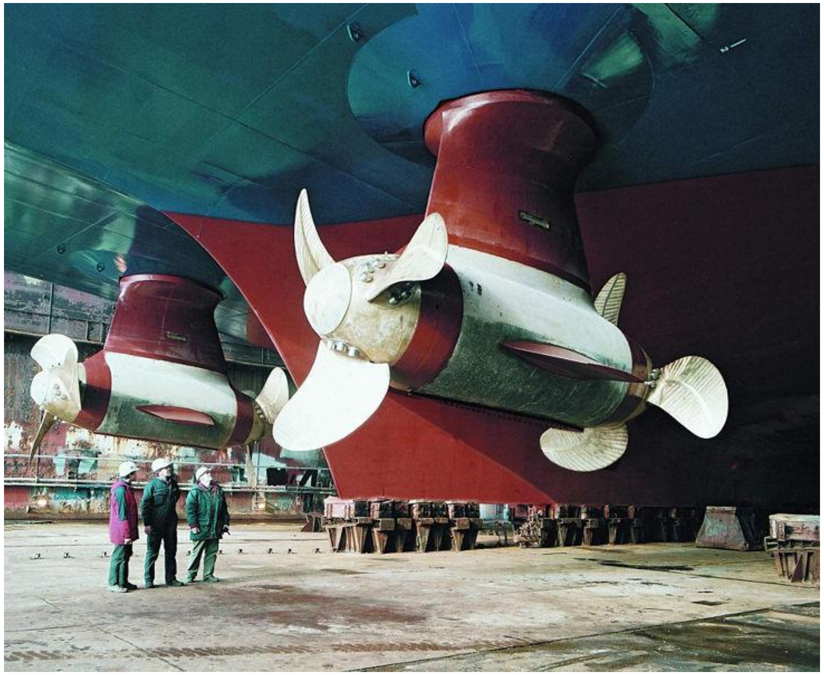
Single Shaft Commercial Electric Drive



Twin Shaft Military IPS Concept

Pods / Azimuth Thruster

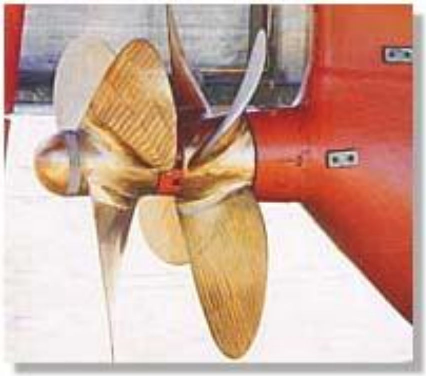
- Increase propulsor efficiency
- Eliminates Shaft Alignment issues
- Maintainability an issue.
- Commonly found on Cruise Ships
  - Commercially available up to the 25,000 HP range
- Pods are not currently used for main propulsion on Naval Warships

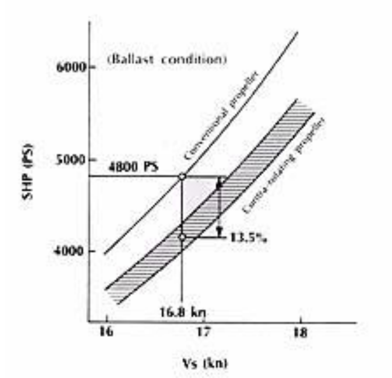


Siemens AG

Contra-Rotating

- Increased Efficiency
  - Recover Swirl Flow
  - 10 – 15% improvement
- Requires special bearings for inner shaft if using common shaft line
- Potential Acoustic Issues
- Recent examples feature Pod for aft propeller





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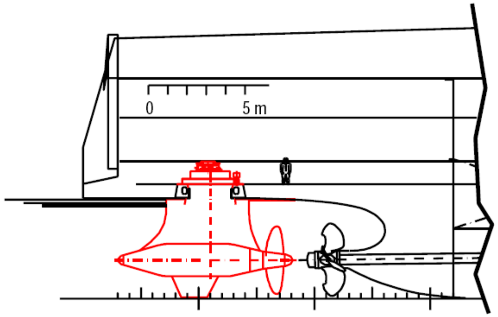

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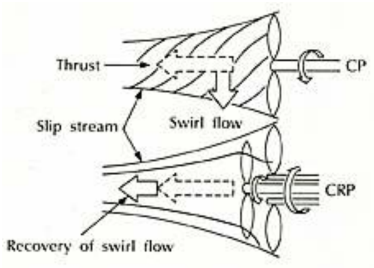


Waterjets

Generally axial flow pumps - direct drive or geared from high-speed diesels or gas turbines

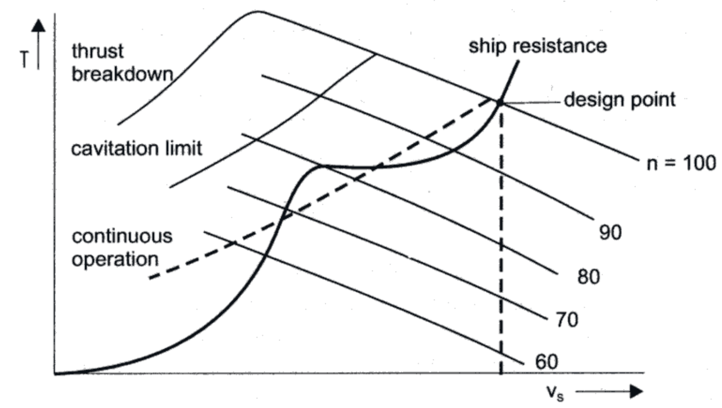
Typically with inlet in the bottom; jet from the transom

Thrust can be obtained from the Momentum Equation

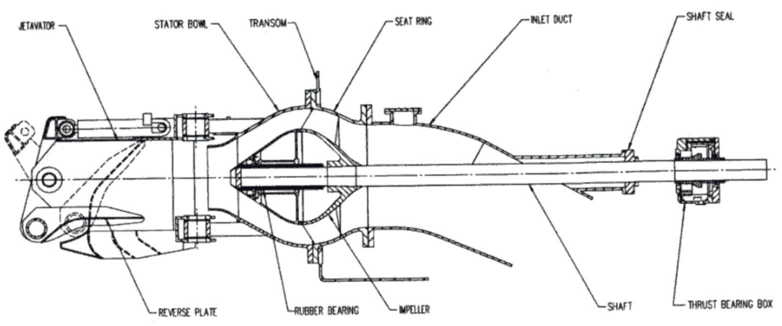
$$T = m(V_{out} - V_{in})$$

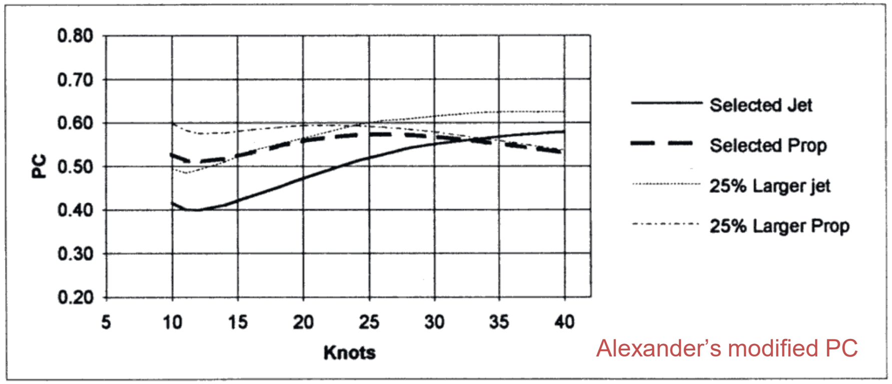
Competitive with propellers above 35-40 knots

Used in high speed ferries, yachts, and naval vessels



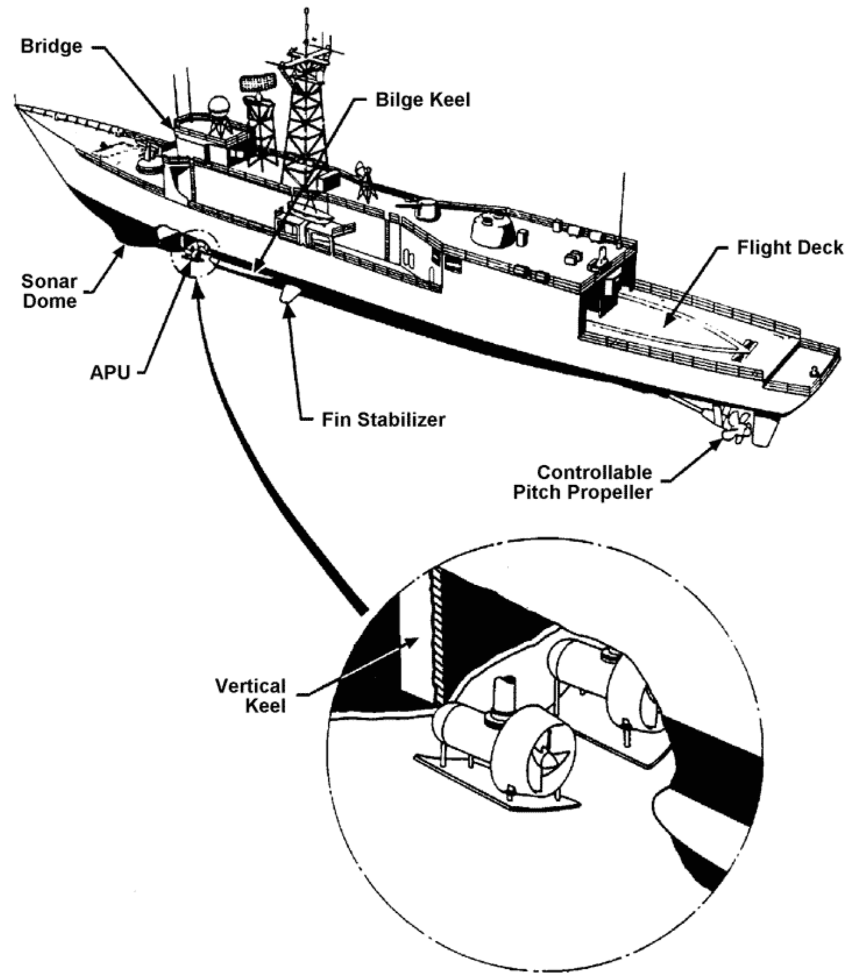
Design matching is done on thrust/resistance rather than power





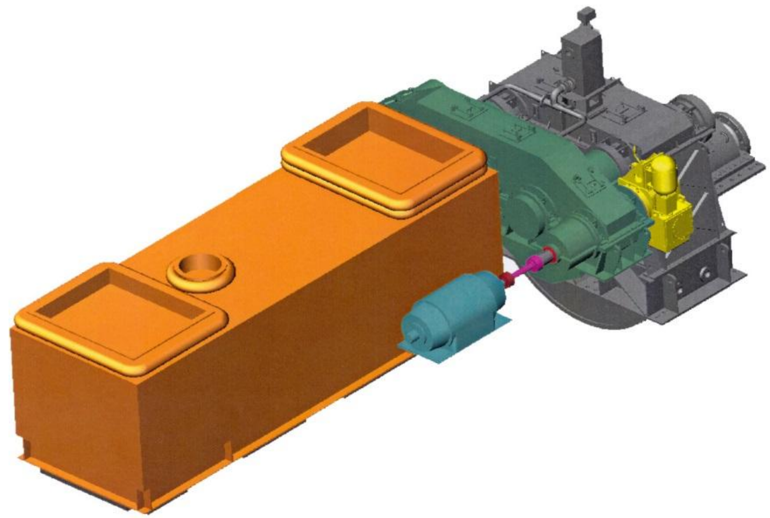
Distributed Propulsion

- Apply Zonal Design concept to Propulsion
  - Weapons effects can damage both shafts in a conventional twin shaft ship
- Forward Propulsors can interfere with bow mounted sonar performance



Hybrid Propulsion

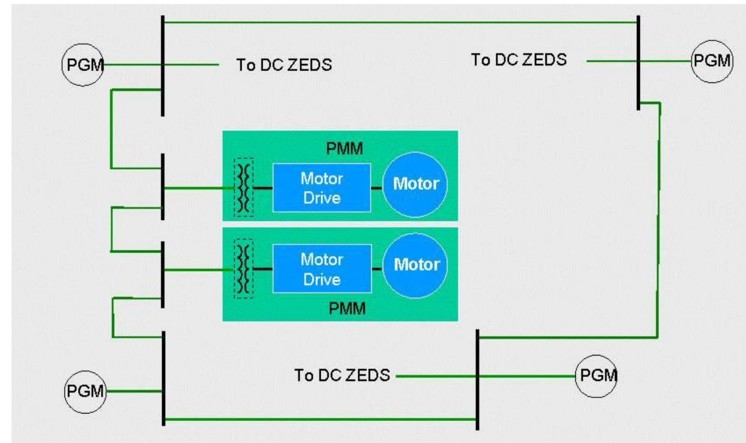
- Combines Mechanical Drive and Electric Drive on same Shaft
- Ideal for ships that spend most of their time loitering, but have a high maximum speed requirement

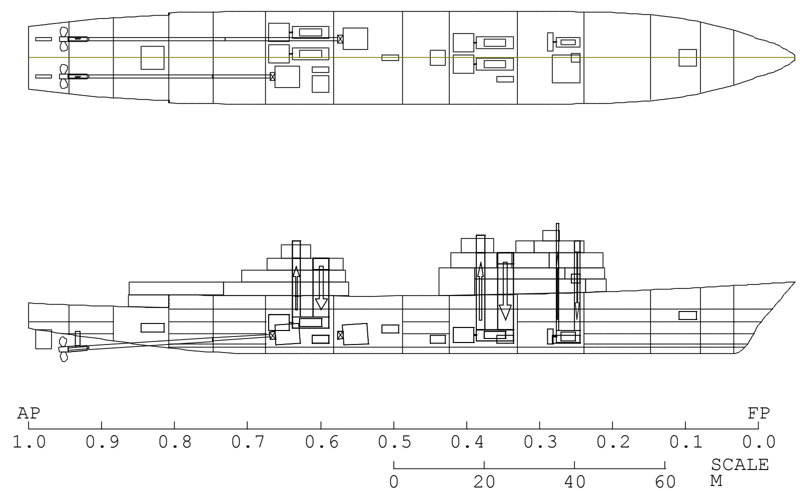


Gas Turbine Mechanical Drive with Auxiliary Propulsion Motor

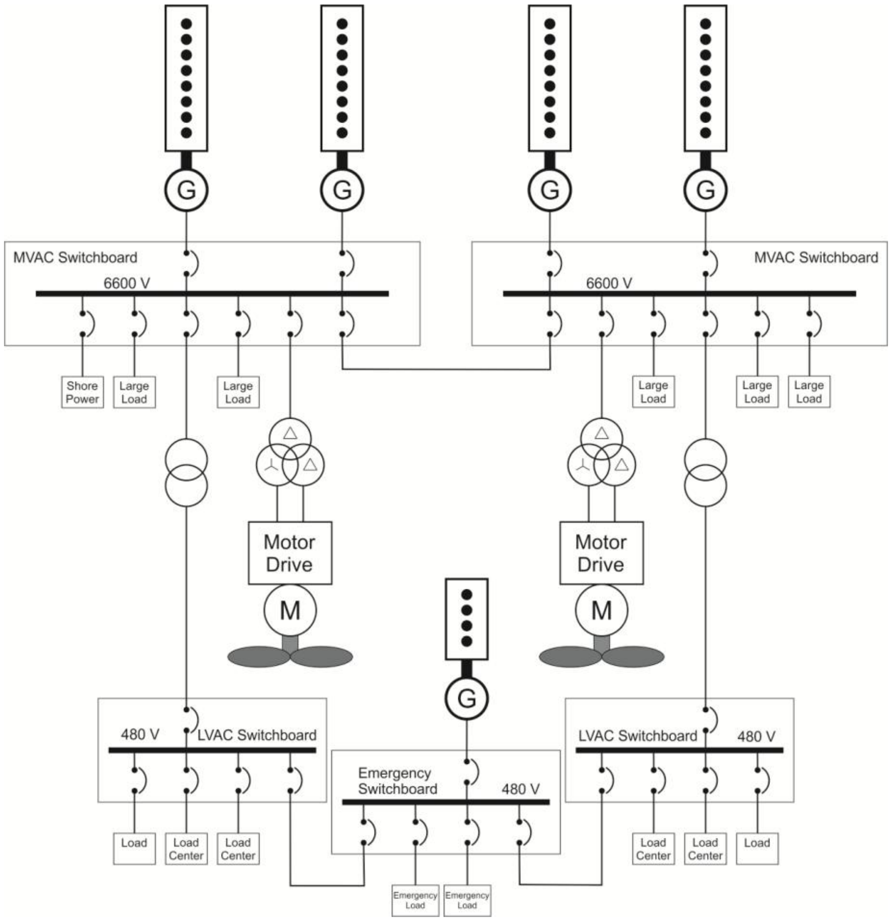
Power Generation Topology and Ratings Guidance

- Choose Efficient Power Generation Modules for the Endurance Condition
  - Typically requires 2 PGMs online or 1 PGM and an ESM for QOS
  - Diesels often attractive for this condition
- For other than emergency PGMs, the minimum rating of a PGM should be the worst case condition sum of all un-interruptible and short term interruptible loads (less 5 minute rating of ESM)
- Consider Gas Turbines for achieving Maximum / Sustained Speed Requirements
  - Lower Weight and Volume
- Power Generation Modules should be longitudinally distributed such that loss of two adjacent zones will leave undamaged zones with sufficient power to service all surviving loads.
- Have at least 2 PGMs that are self starting
  - Locate as far apart as possible for survivability considerations
  - Serve as Emergency Generators
  - Each should be rated to at serve all emergency loads plus have ability to start all other PGMs in sequence.
    - Emergency loads are a subset of “vital” loads

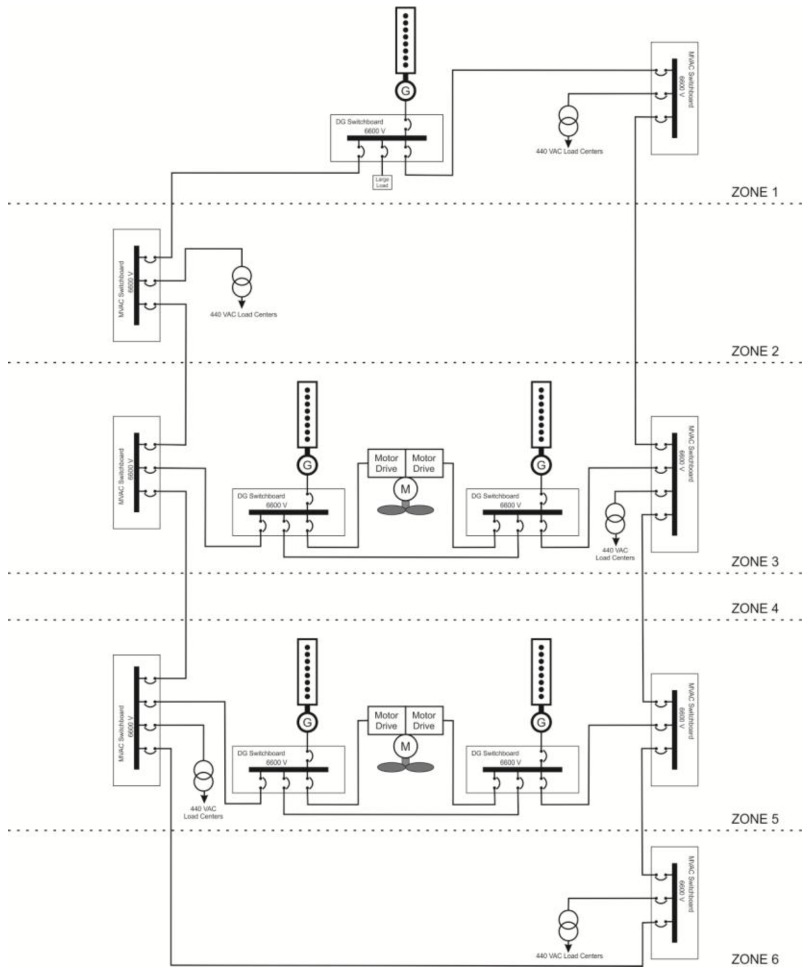


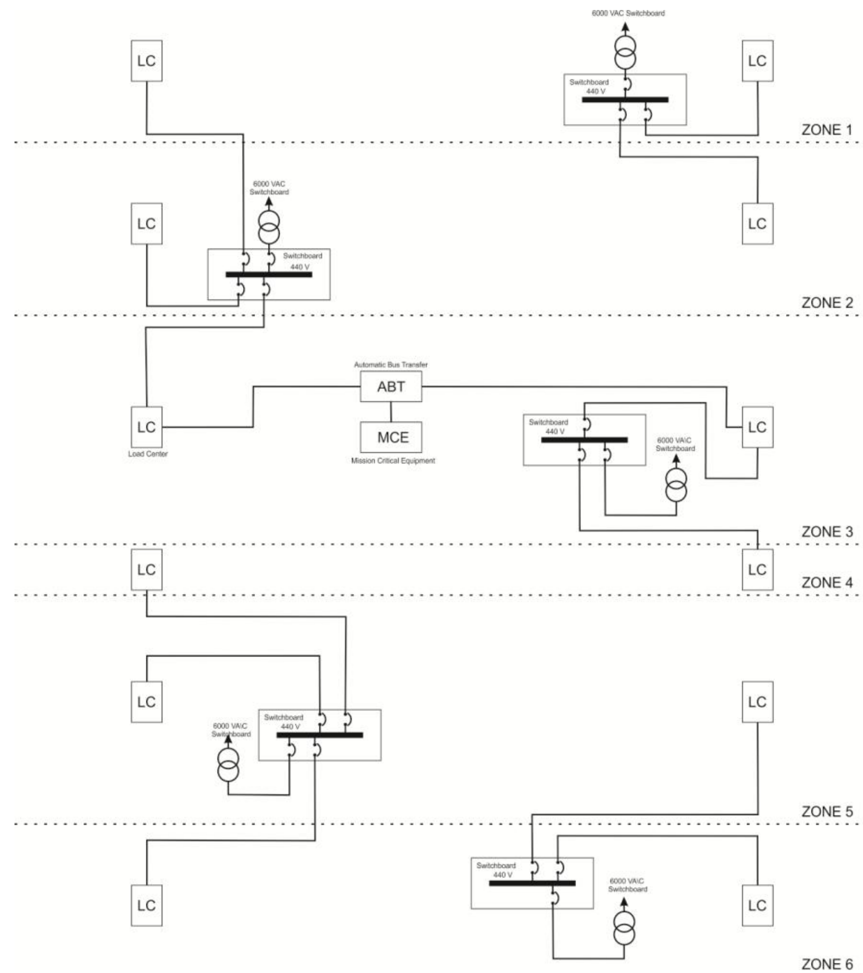


Commercial IPS Example



MVAC Zonal Example





Power Generation Considerations

- Past Studies have shown that **4 to 6 prime movers** typically provide the best trade-off of cost, weight, survivability, and Quality of Service
- For QOS, must always have **at least two sources of power on-line** (one may be energy storage module)
  - The rating of the smaller source should be greater than the sum of the un-interruptible and short-term interrupt loads.
- For the Endurance conditions, the on-line power generation modules should be operating in the **flat tail of the SFC curve**
  - Each type of prime mover has a minimum load for efficient operation (can range from 25% to 80%)
- Prime Movers paralleled via ac power (and not providing propulsion power) should **not be loaded more than 95%** to account for dynamics in load sharing and variance of the instantaneous ship service power around its average value
  - The percentage for sharing via dc power has not yet been determined but will likely not be below 95%.
  - With suitable controls, a propulsion motor module can provide the needed flexibility to deal with ship service power variance.
- For Survivability, **Sufficient separation of prime movers** should be provided such that the loss of generation in any two adjacent zones should leave enough generation capacity to service all remaining non-propulsion loads in the remaining undamaged zones.
  - Some Propulsion capability should remain.

Diesel vs Gas Turbine

Table 4.1 Typical Performance Parameters of Medium-Speed Diesel Engines and Marine Gas Turbines (2001) [adapted from 1]

Data	Medium-speed Diesels	Aero-derivative Gas Turbines	Industrial GT35	Rolls-Royce WR21
Process/cycle	4-stroke	simple cycle	simple cycle	advanced cycle
Construction	trunk piston	two-shaft	two-shaft	two-shaft
Output power range [kW]	500-35000	6000-41000	17000	24000
Output speed [rpm]	300-1000	3600-7000	3300	3600
Fuel type	HFO or MDO	MGO or JP5	MDO or IF30	MGO
Specific fuel rate [g/kW h]*	170-210	240-280	260	200
Specific air rate [kg/kW h]	6-9	10-15		10.5
Specific NOx Emission [g/kW h]	10-18	2-5	2	3
Specific mass [kg/kW]	5-20	1.0-1.4	1.5-2.0	1.8
Specific volume [dm^3/kW]	4-28	2.5-4.5	6.0	4.1
Specific cost [$/kW]	L: 240-360	200-310		515
* ISO standard on MDO	V: 190-310			

<u>Diesels:</u>

- Fast Starting
- Fuel Efficient
- Smaller intakes
- Smaller uptakes
- Greater Variety

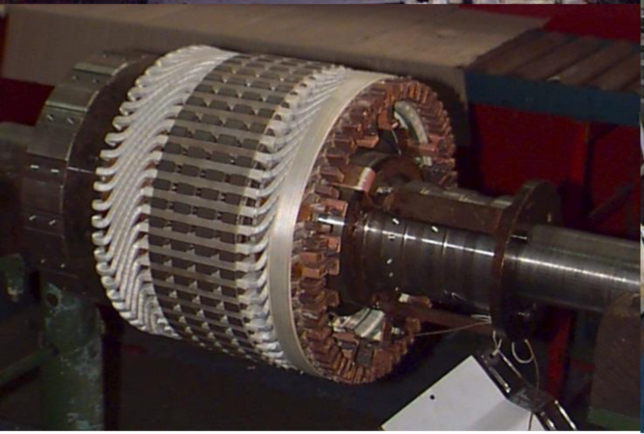
<u>Gas Turbines:</u>

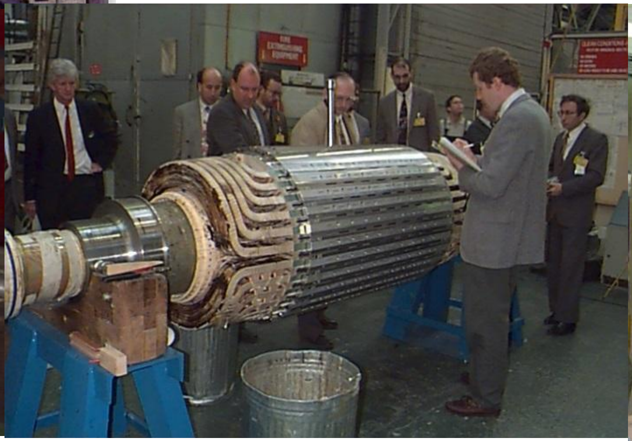
- Power Dense
    - Weight
    - Volume
- Lower emissions

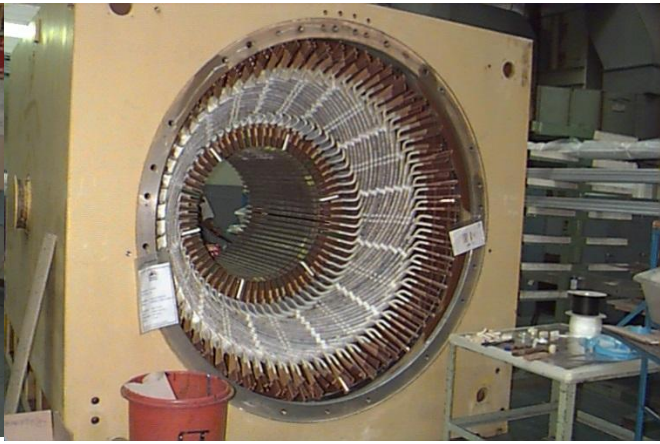
IPS Propulsion Generator

- 21 MW - 26.25 MVA
- 4160 V - 3 Phase
- 60 HZ - .8 Pwr Fctr
- 2 Pole - 3600 RPM
- 97 % Efficiency
- 50,050 KG
- 3.4m(H) x 4.7m(L) x 4m(W)
- Mfd. by: Brush Electric Machines Company (UK)

Courtesy of Timothy J. McCoy © 2003







Generation Requirements

Speed-Power (knots - SHP) Curve

Motor / Motor Drive Efficiency Curve

Speed – Propulsion Power (Electrical) Curve

Prime Mover Specific Fuel Consumption Curves

Total Load Estimate

Margin and Service Life Policy

Endurance Information
- Endurance Speed and Range

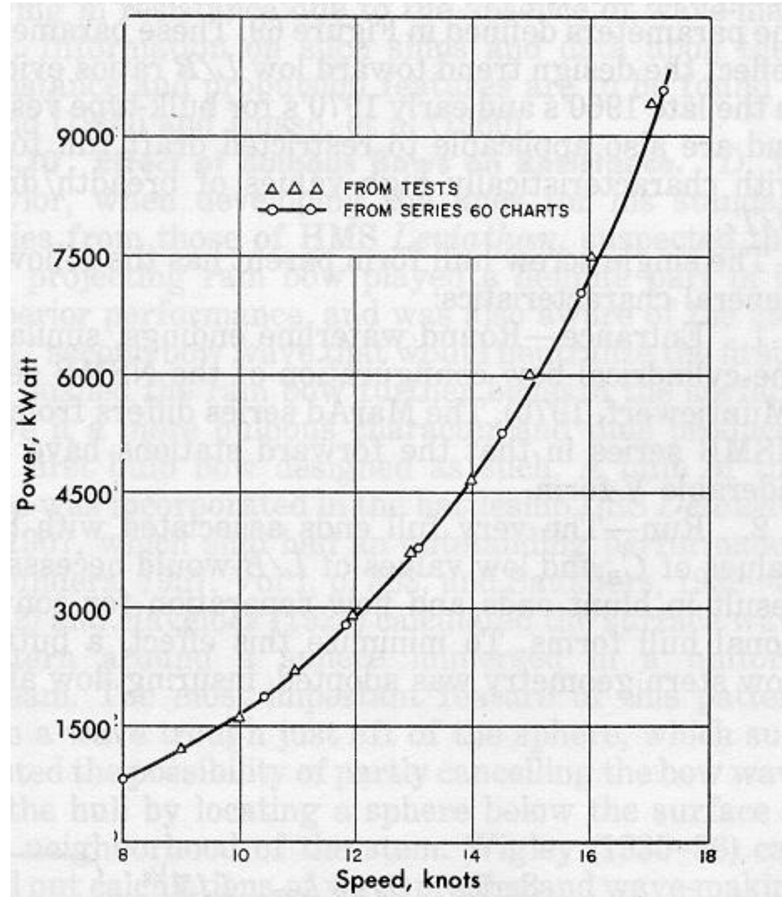
or

- Speed -Time Profile & Endurance Time

Generation Requirements
- Maximum Margined Load
- Un-interruptible, Short Term Interrupt, and Long Term Interrupt Power Requirements per operating condition
- Endurance Power requirements

Speed – Power Curve

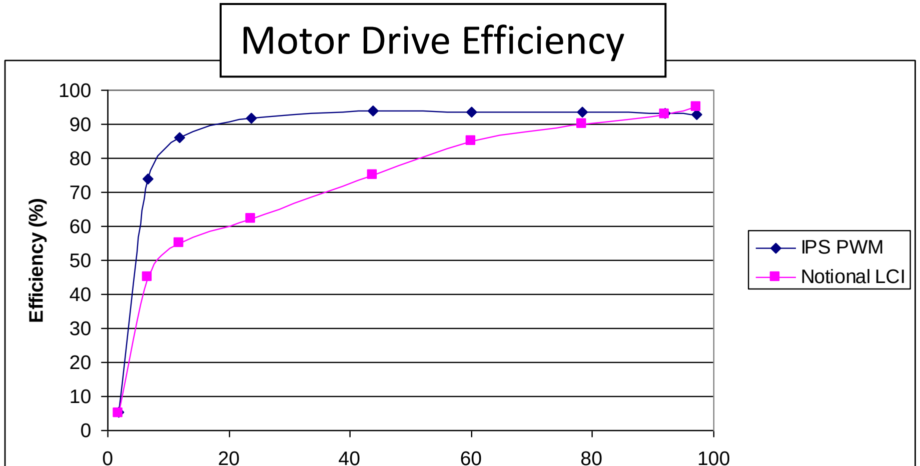
- How to calculate
  - Bare Hull Drag
    - Synthesis and specialized computer Tools
    - Standard Series
    - Scaling from existing ships
  - Propeller Characteristics
  - Power Margin Factor
  - Ship Propeller interaction
  - Bearing and Shafting Efficiencies
- Standard Assumptions
  - Clean Bottom
  - Calm Seas
  - Deep Water
  - Full Load Displacement



Comparison of P_E from model tests of a bulk carrier with estimate from Series 60 charts.

Motor and Motor Drive Efficiency Curves

- Where to Find
  - Manufacturer's Data
  - Generalized estimates
- A healthy skepticism with respect to data is always good.



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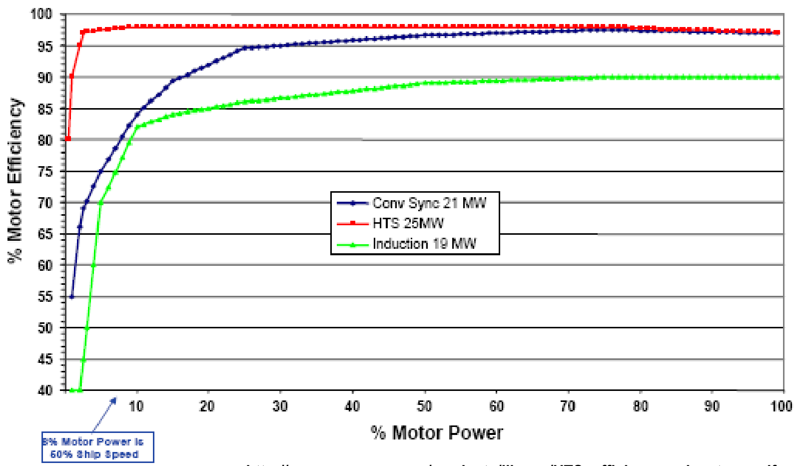
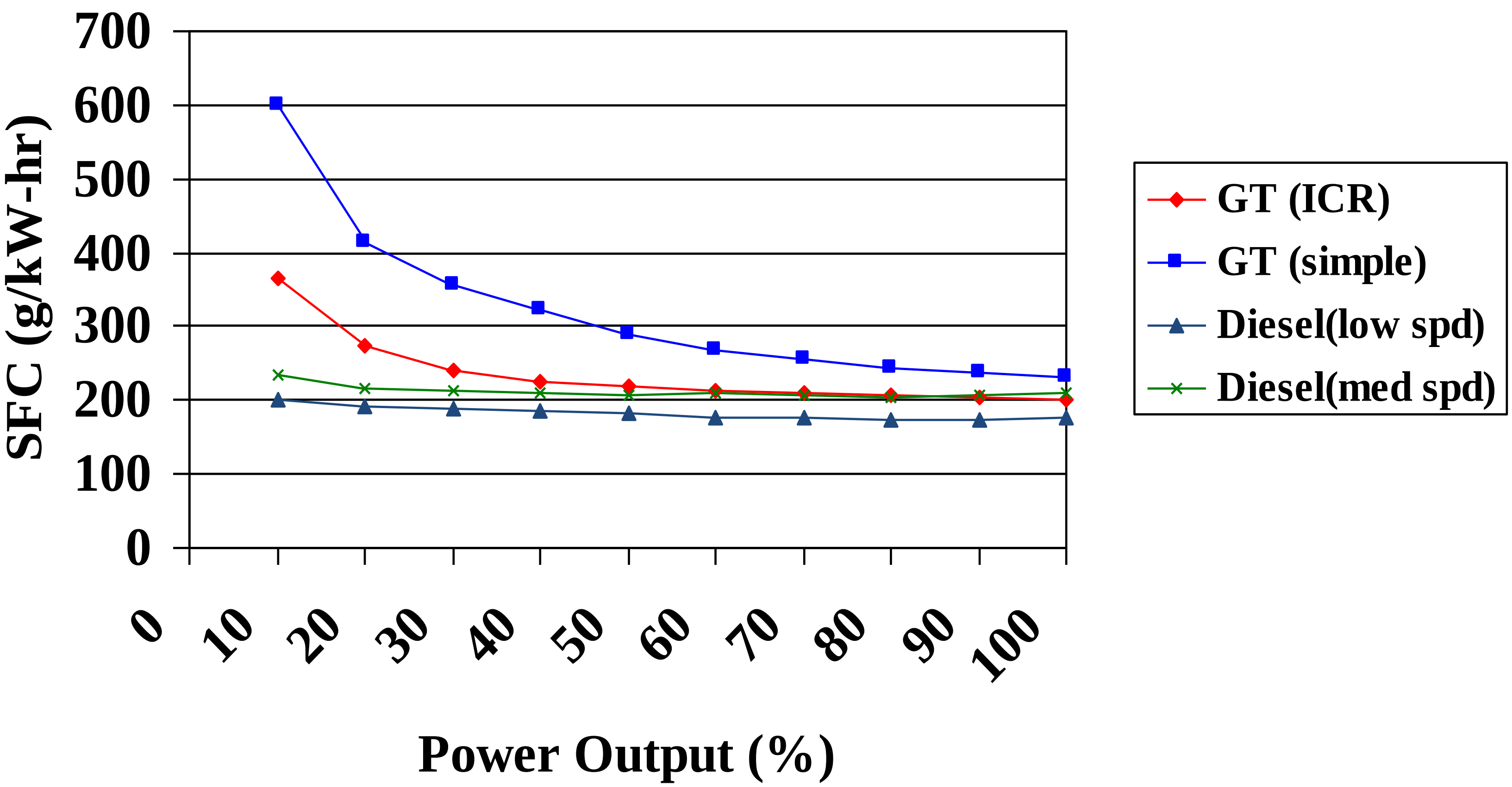


http://www.amsuper.com/products/library/HTS_efficiency_advantage.pdf

Prime Mover Specific Fuel Consumption



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How do you Estimate the Total Ship Service Load?

- Analogy & Parametric
  - Scale from other ships
- Synthesis Tool
  - Let embedded routines do the estimate
- EPLA – Load Factors (See DDS 310-1)
  - “Works” only if you have a large number of relatively small loads.
  - Must account for “Large Loads”, starting large motors, and inrush current.
  - Appropriate for large ships power generation sizing
  - Appropriate for early stage design of in-zone components
- EPLA – Stochastic Method (See DDS 310-1)
  - Calculate probability of power load for different operating conditions.
  - Determine required generation capability to achieve an acceptable probability for meeting demand based on Quality of Service
- EPLA – Modeling and Simulation (See DDS 310-1)
  - Quasi-static modeling of loads and controls

Margin and Service Life Allowance

TABLE 2-1
MARGINS (PERCENT) FOR SHIP SERVICE AND EMERGENCY GENERATING PLANTS

Ship Type	End of Preliminary Design	End of Contract Design	Service Life (30 yrs) **Allowance**
Aircraft Carriers	30	26	20
Surface Combatants	44	34	20
Amphibious Warfare, Mine Warfare, Auxiliaries and Support Craft	33	28	20
Tenders	50	40	25
High Performance Ships	55	38	15

NOTE: SLA does not apply to
- **Propulsion plant**
- **Steering systems**
- **Replenishment systems**
- **Mechanical handling systems**
- **Deballasting systems**

NOTE: Margins and SLA only apply to Ship Service Loads

Includes Service Life Allowance

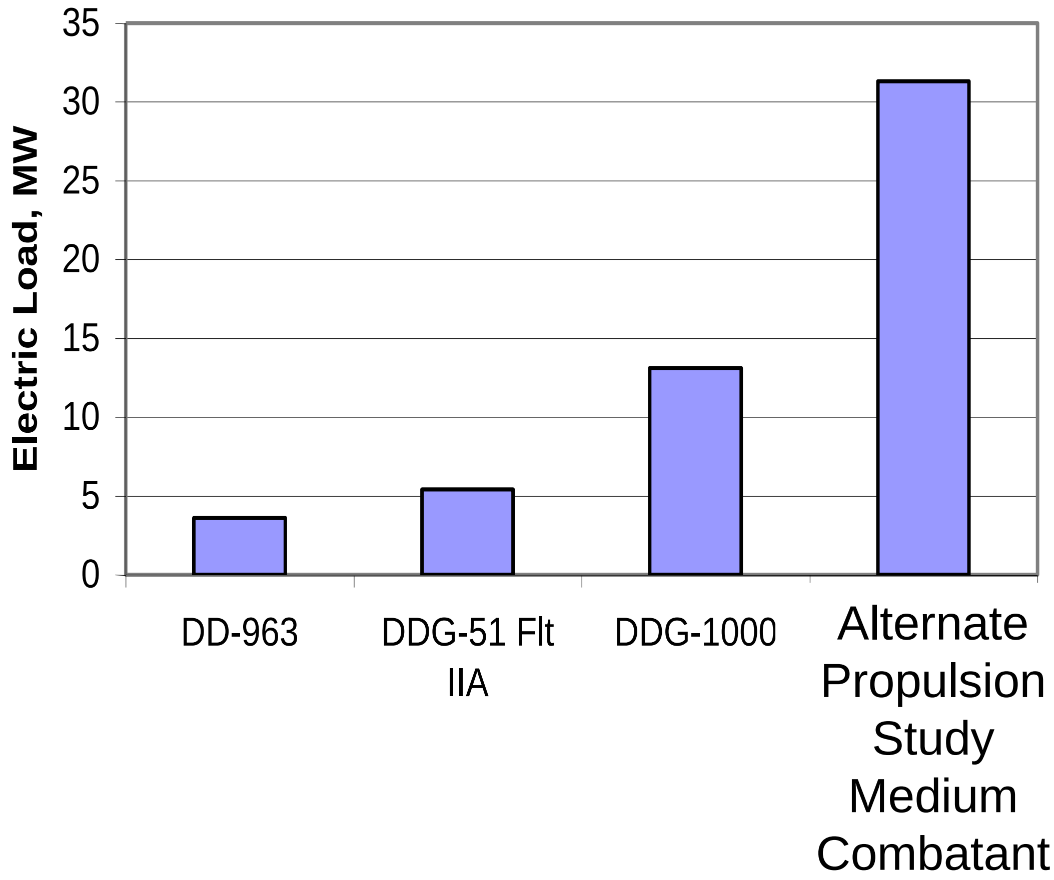
Endurance

- Desire for Power Generation Modules and Propulsion Motor Modules to be efficient for endurance conditions
  - Endurance calculations size the fuel tanks and have a major impact on Full Load Displacement'
- DDS 200-1 Rev 1 Defines three possible endurance conditions
  - Economical Transit
  - Surge to Theater
  - Operational Presence

160222-N-MD297-180: DDG 82 and T-AO 200 (USN Phot by Huey D. Younger Jr.)

Growth of Mission System Loads

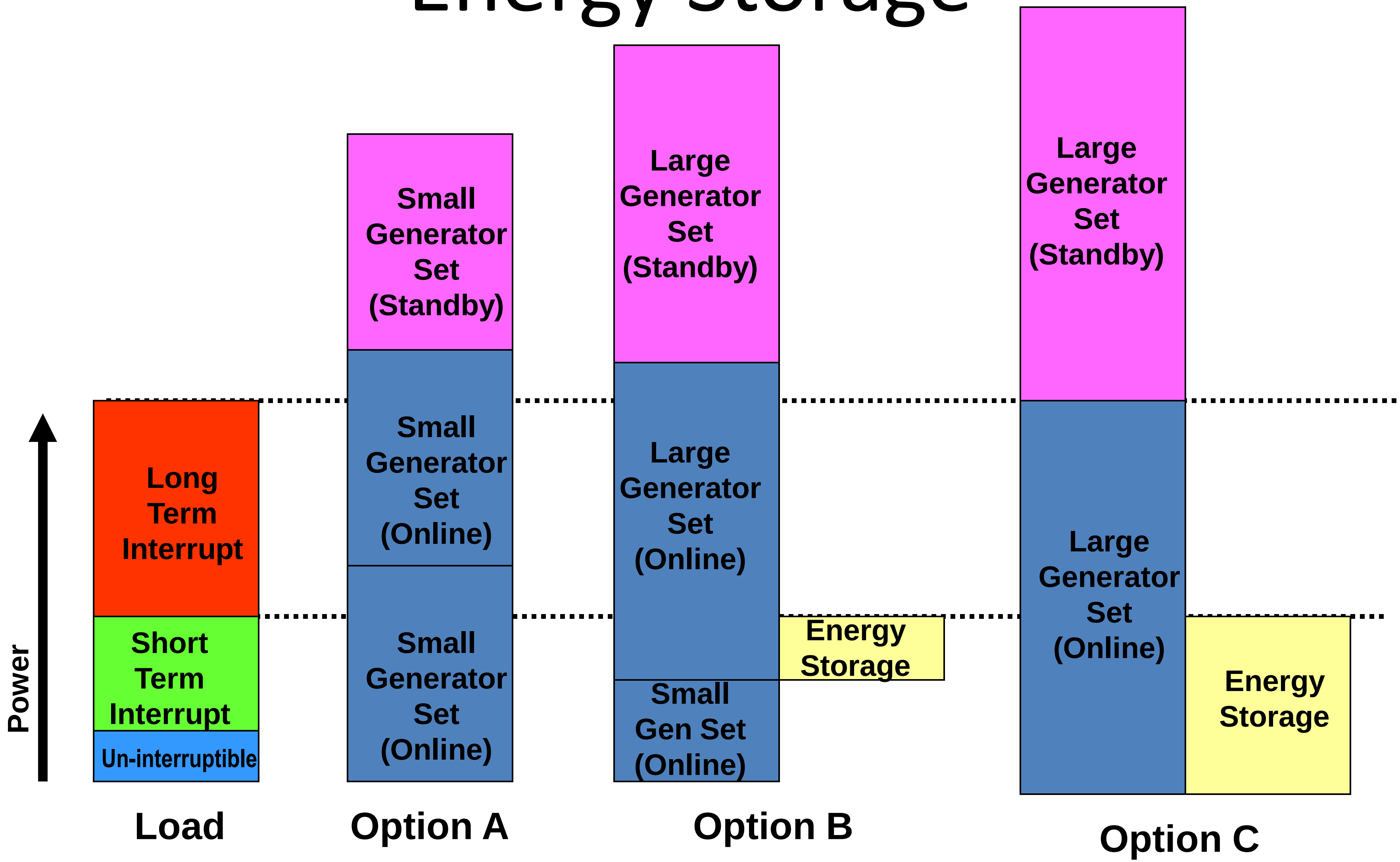
- Future non-mobility Mission Systems will likely drive fuel requirements more than propulsion
- Endurance Range and Speed may no longer be appropriate for sizing fuel tanks



Calculating Total Power Generation Required

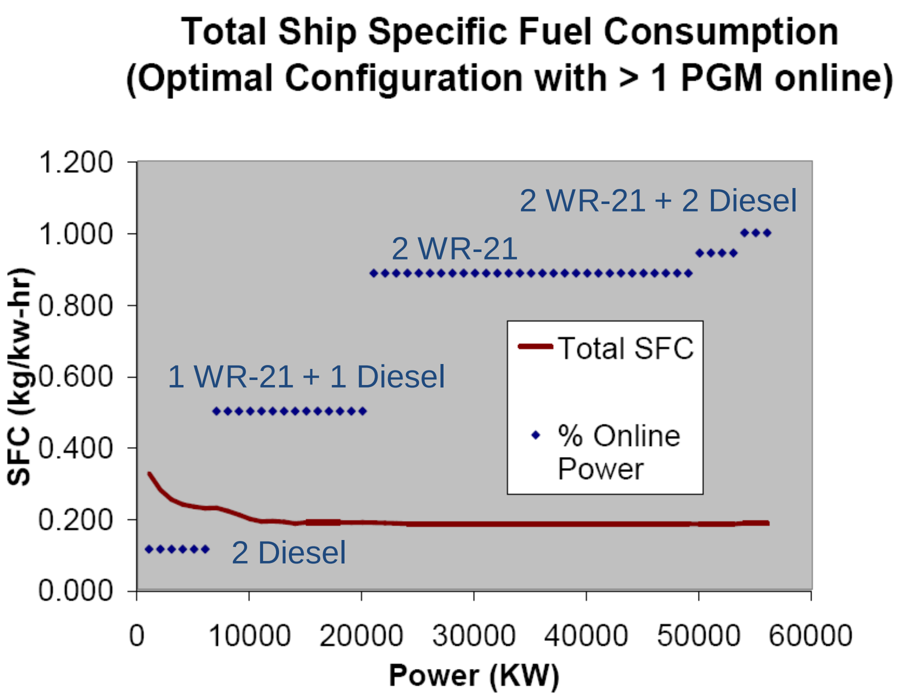
- Maximum Propulsion Power
  - Calculate the Shaft Power for the Sustained Speed (include Power Margin Factor)
  - Multiply by 1.25 (definition of sustained speed)
  - Divide by the efficiency of the Propulsion Motor Module. (convert to electrical power)
- Calculate Propulsion Power at other condition speeds
  - Include Power Margin Factor and correct for PMM efficiency
- For each operational condition, add the maximum ship service electrical load to the appropriate propulsion power
  - Include margin and service life allowance in the ship service electrical load

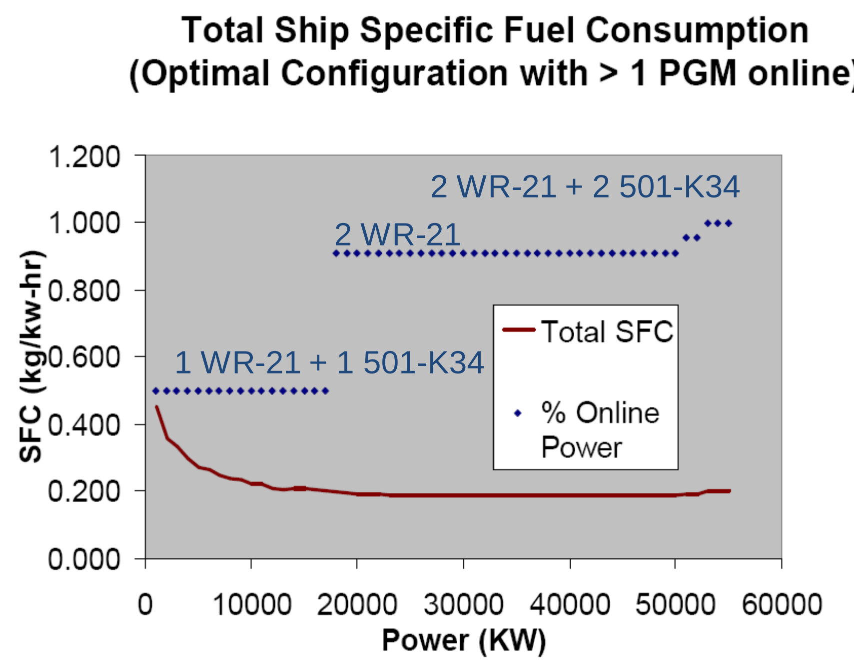
Power Generation Sizing vs. Energy Storage



Power Generation Fuel Consumption

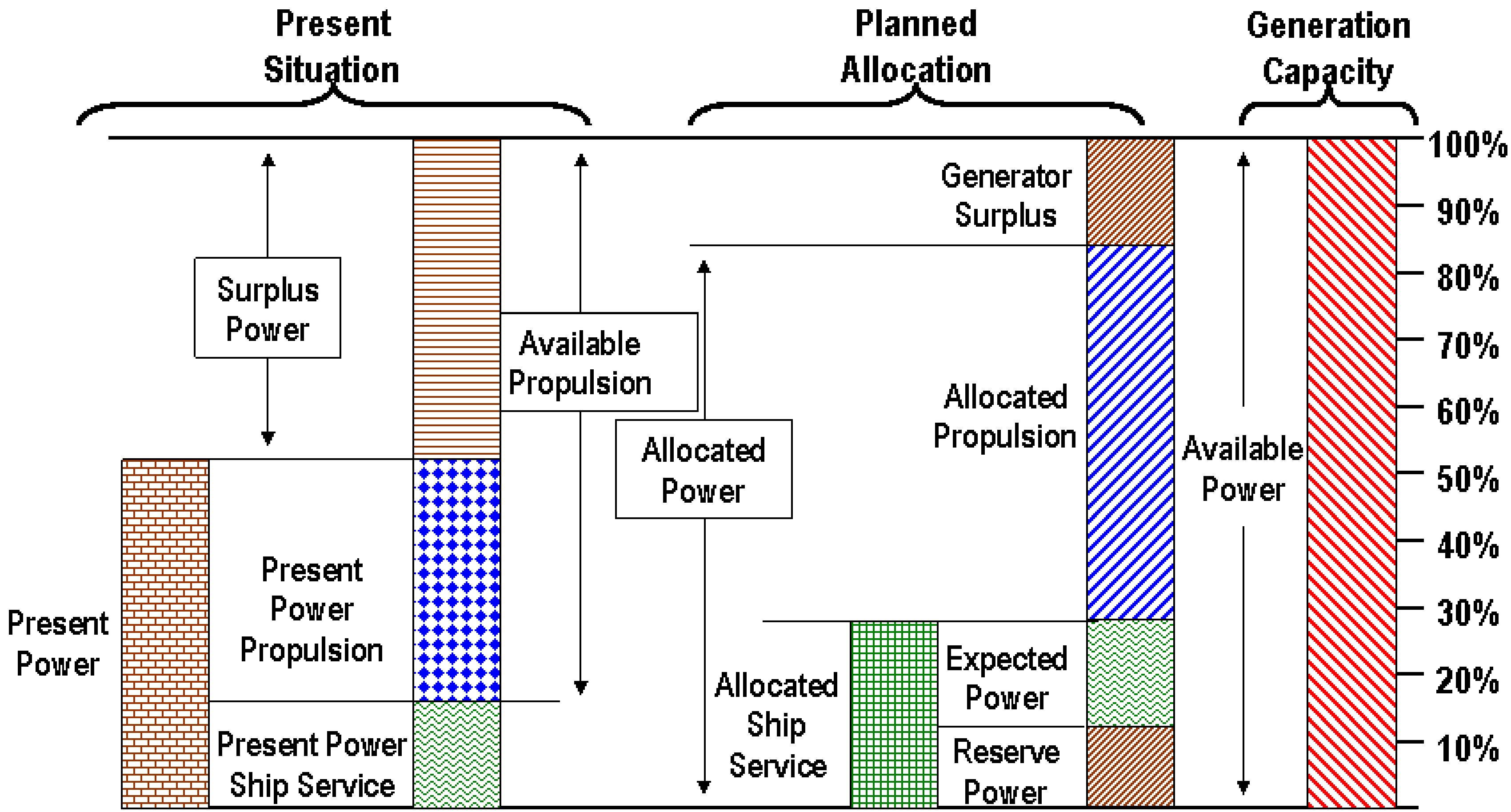
- Ship Fuel consumption rate depends on plant line-up and PGM efficiencies





- Plant line-up must consider QOS, fault current, and survivability
- Usually requires at least 2 prime movers on line (unless sufficient Energy Storage is available)

Power Management

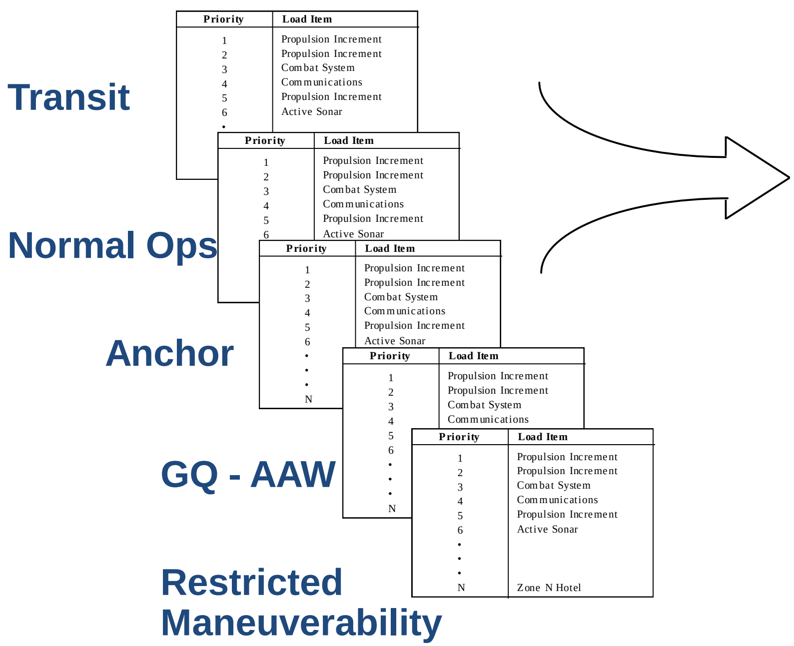


Load Shed Strategy

- QOS Load Shedding
  - Shed long-term interrupt loads first – regardless of mission priority.
  - Bring stand-by generator online and restore long-term interrupt loads before 5 minutes
- Mission Priority Load Shedding
  - If unable to restore long-term interrupt loads within 5 minutes, or if shedding long-term interrupt loads is not sufficient
    - Shed the lowest mission priority loads regardless of QOS category (typically propulsion allocated power)
    - At five minutes, restore those long-term interrupt loads with a higher mission priority by shedding other lower mission priority loads.

Mission Prioritization Load Shedding

Operational Scenarios



Load Priorities

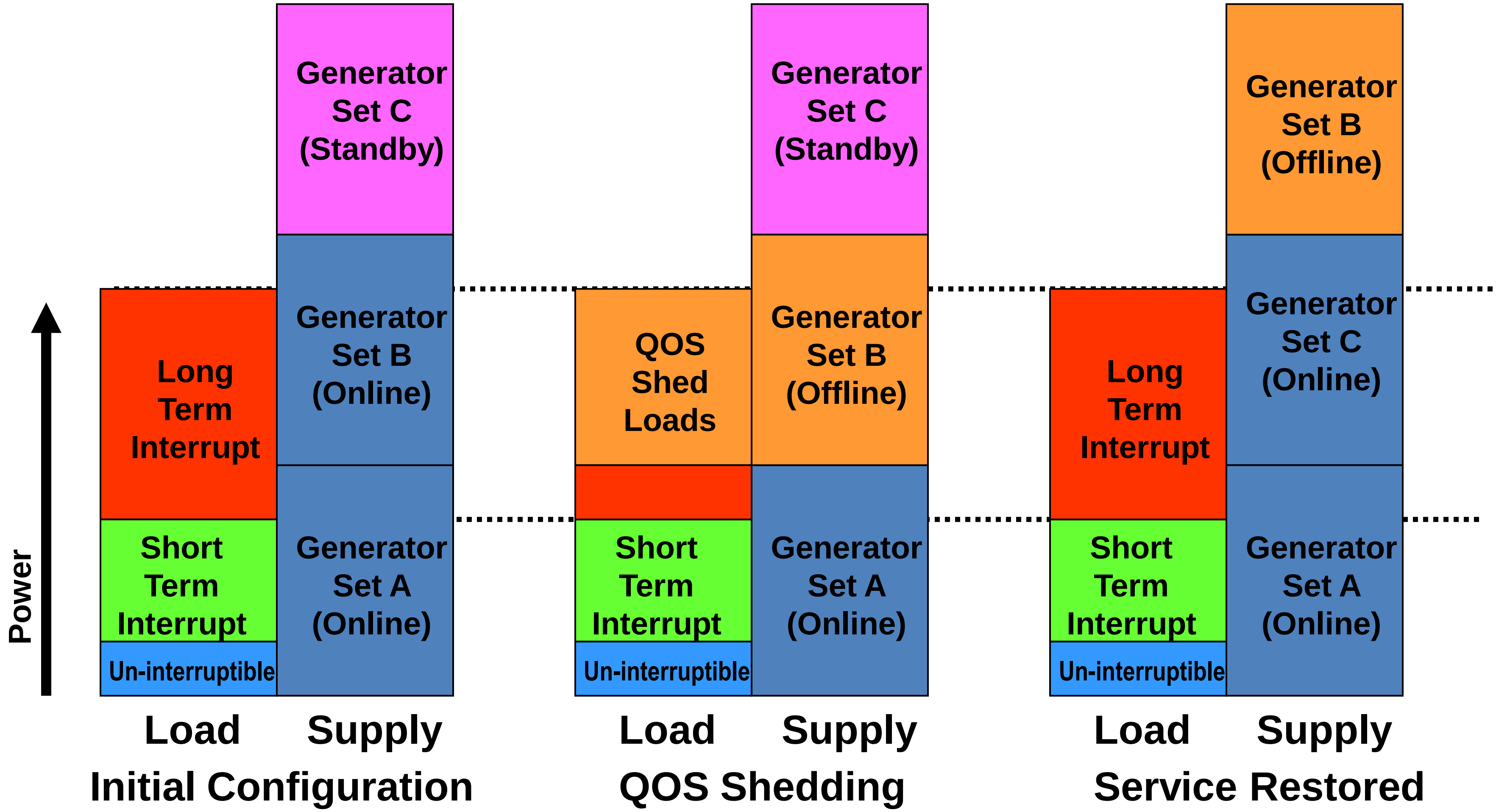
Priority	Load Item
1	Propulsion Increment
2	Propulsion Increment
3	Combat System
4	Communications
5	Propulsion Increment
6	Active Sonar
•	
•	
•	
N	Zone N Hotel

Load Characteristics Definition

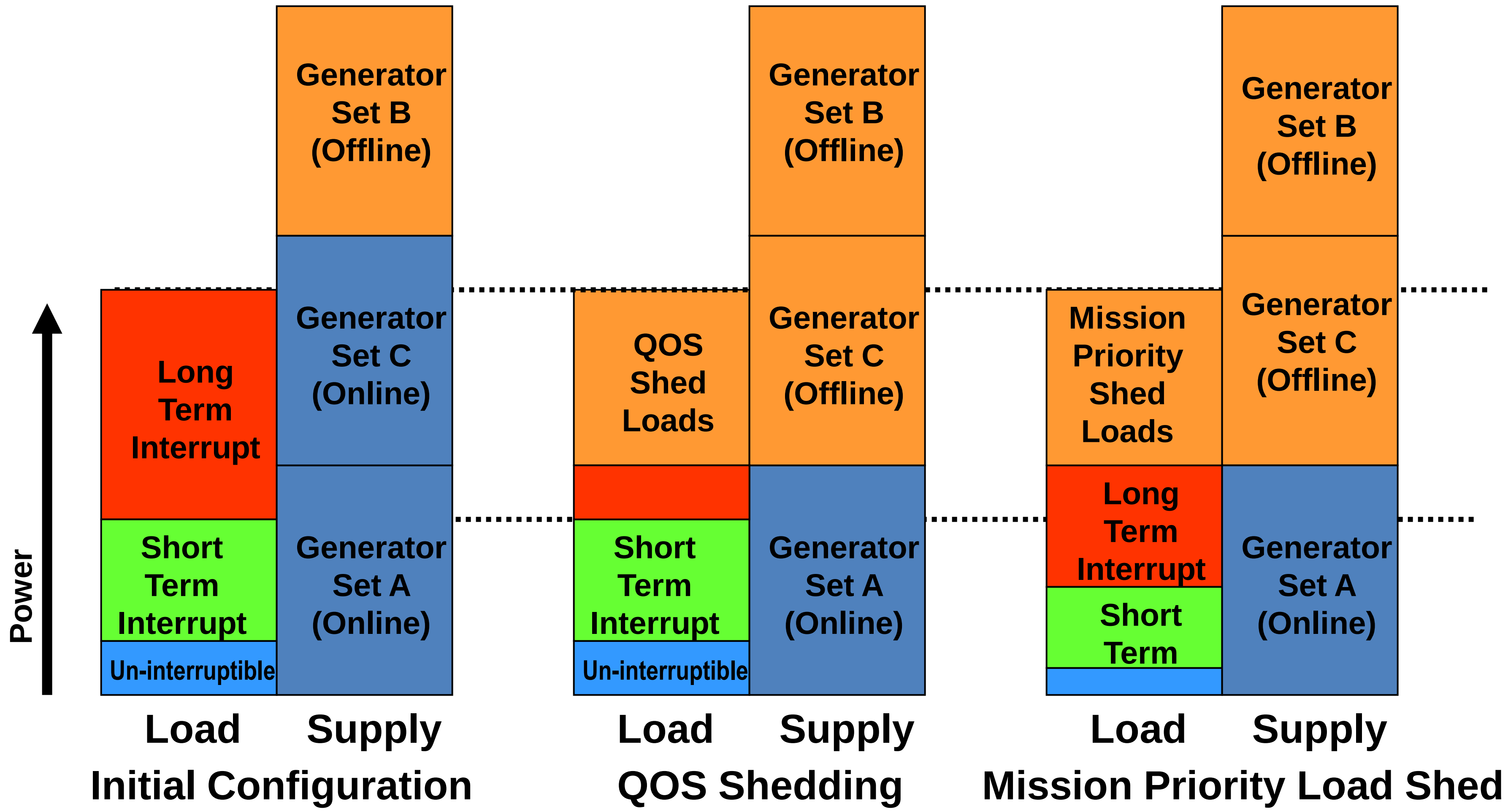
	Steady State		Startup			
Load Item	Allocated Pwr (KW)	Allocated Pwr (KVAR)	Allocated Pwr (KW)	Allocated Pwr (KVAR)	Level of Control	Location
Combat Sys	150	N/A	150	N/A	Open / Close	Zone X/PCM2/ID4 etc
Comms	100	N/A	100	N/A	Open / Close	
Active Sonar	200	N/A	200	N/A	Open only	
Zone 1 Hotel	50	N/A	50	N/A	Open only	
Zone 2 Hotel	75	N/A	75	N/A	Open / Close	
Zone N Hotel	25	N/A	25	N/A	Open only	
PMM-1 (A)	1000	500	1000	100	N/A	

- Propulsion power broken down into incremental discrete loads.
- Equipment which is off-line is allocated no power.
- Operational Scenario Descriptions (OSDs) do not include PGM line up.

Example: Loss of First Generator



Example: Loss of Second Generator



MVDC Architectures

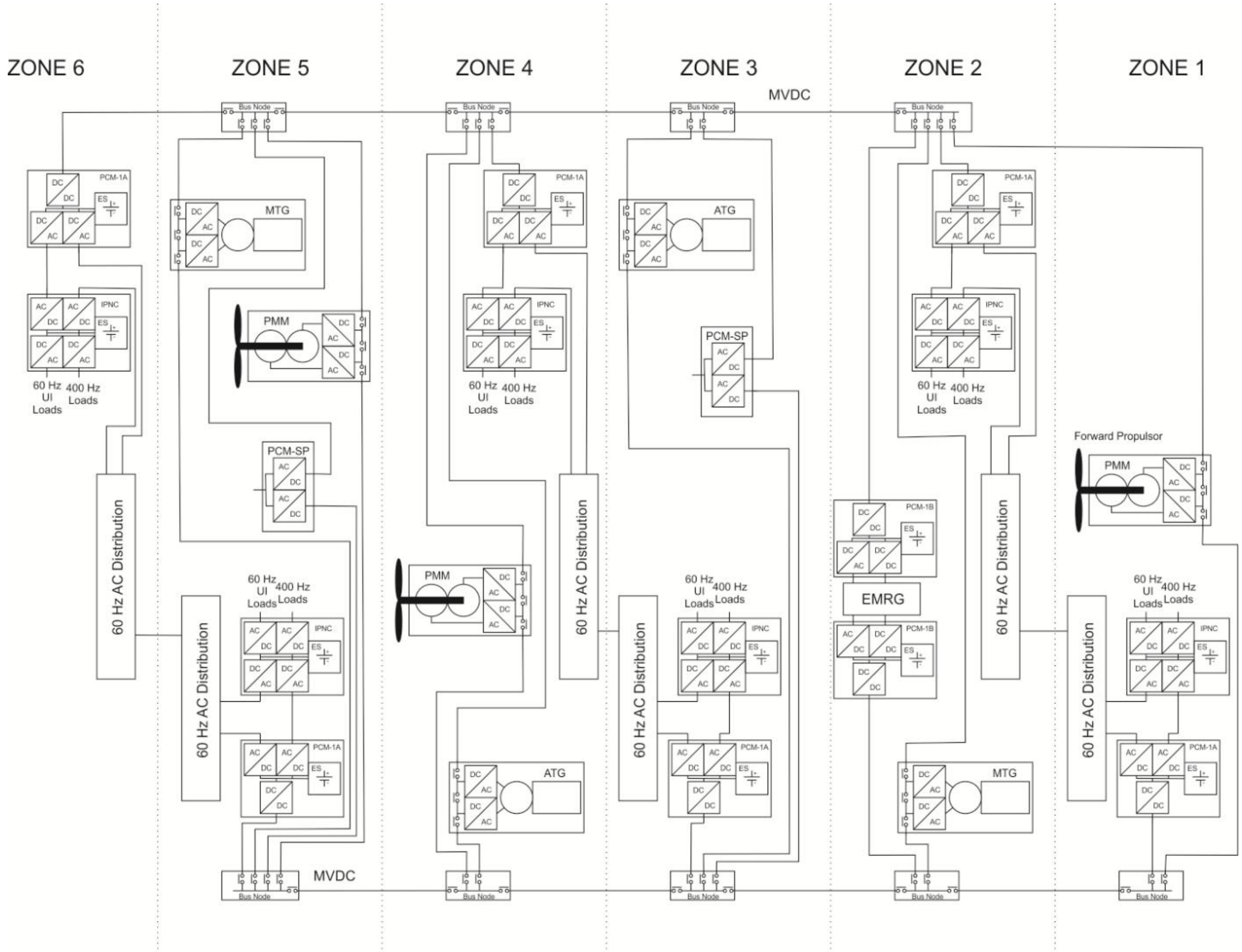
Why Medium Voltage DC?

- Decouple prime mover speed from power quality
  - Minimize energy storage
- Power conversion can operate at high frequency – Improve power density
- Potentially less aggregate power electronics
  - Share rectification stages
- Cable ampacity does not depend on power factor or skin effect
- Power Electronics can control fault currents
  - Use disconnects instead of circuit breakers
- Acoustic Signature improvements
- Easier and faster paralleling of generators
  - May reduce energy storage requirements
- Ability to use high speed power turbines on gas turbines

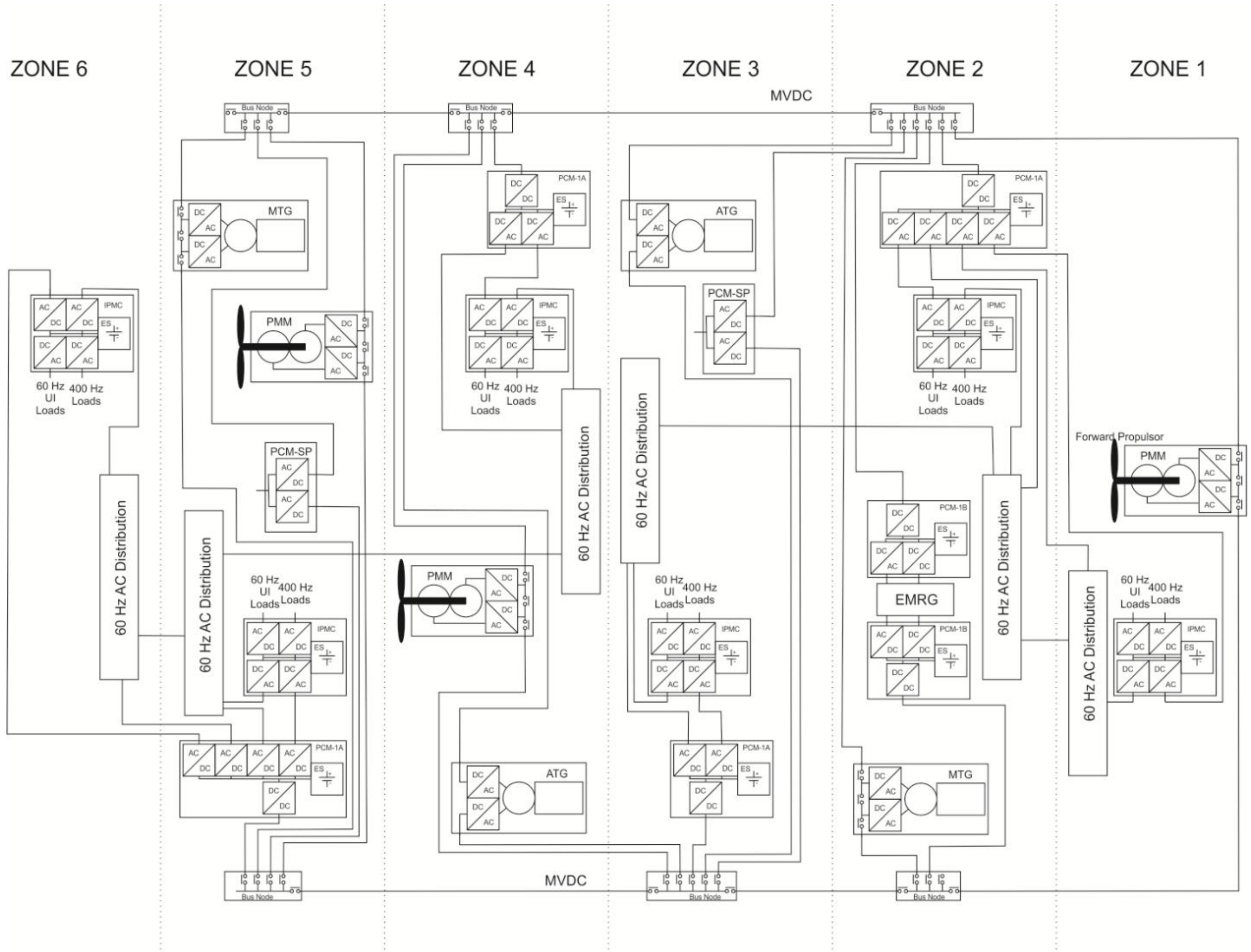
Affordably meet electrical power demands of future destroyer

An AC Integrated Power System would likely require future destroyer to displace greater than 10,000 mt

MVDC Reference Architecture



Alternate MVDC Architecture

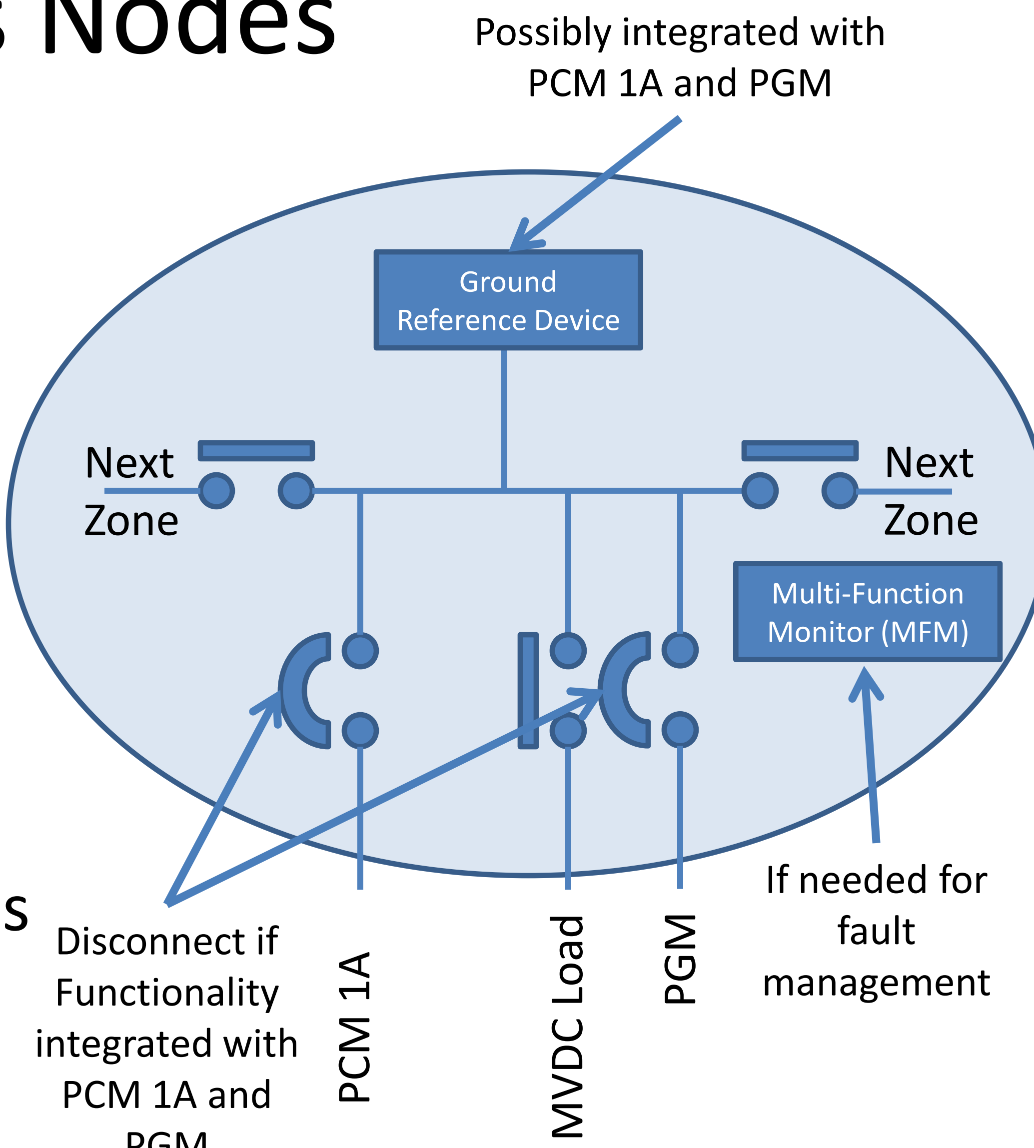


MVDC Voltage Standards

- MVDC nominal voltages based on IEEE 1709
  - 6000 VDC
  - 12000 VDC
  - 18000 VDC
- Current levels and Power Electronic Devices constrain voltage selection
  - 4000 amps is practical limit for mechanical switches
  - Power electronic device voltages increasing with time (SiC will lead to great increase)
- For now, 12000 VDC appears a good target …
- Power Quality requirements TBD

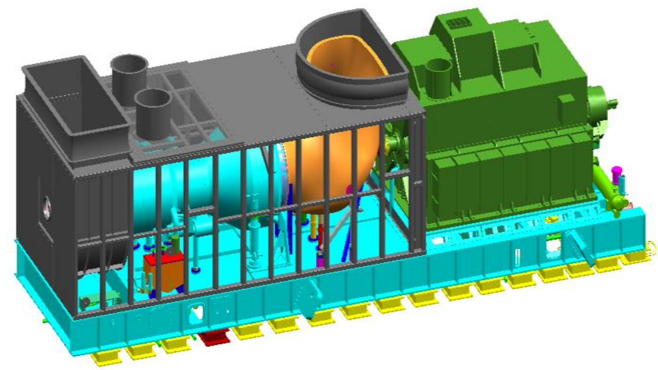
Bus Nodes

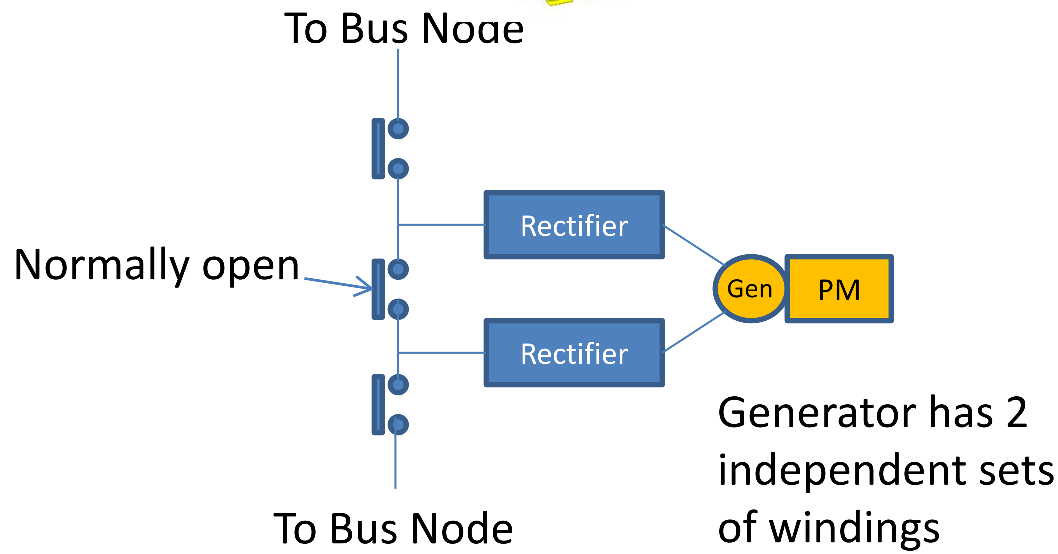
- Segment MVDC Bus
  - Disconnects
- Isolate loads
  - Disconnects
- Isolate sources
  - Breaker
  - Disconnect if Breaker functionality in source
- Establishes Ground Reference for MVDC Bus
  - If functionality not provided in source



Power Generation Modules

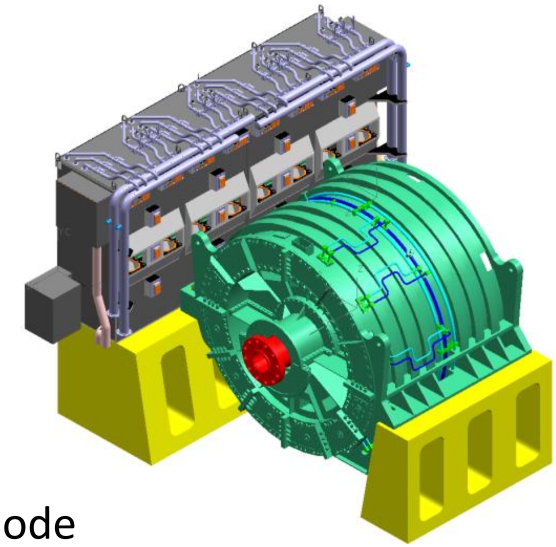
- Split Windings
  - Reduced Impact on prime mover due to fault on one MVDC bus
  - Simplifies "odd number of generators" dilemma
    - May enable reducing ampacity of MVDC bus
- Consider Fuel Cells in the future

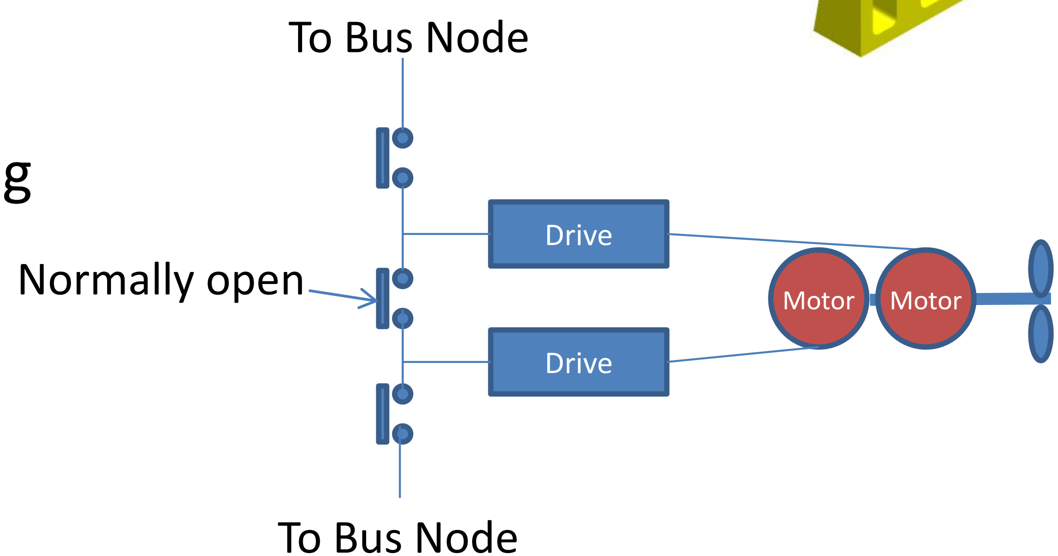




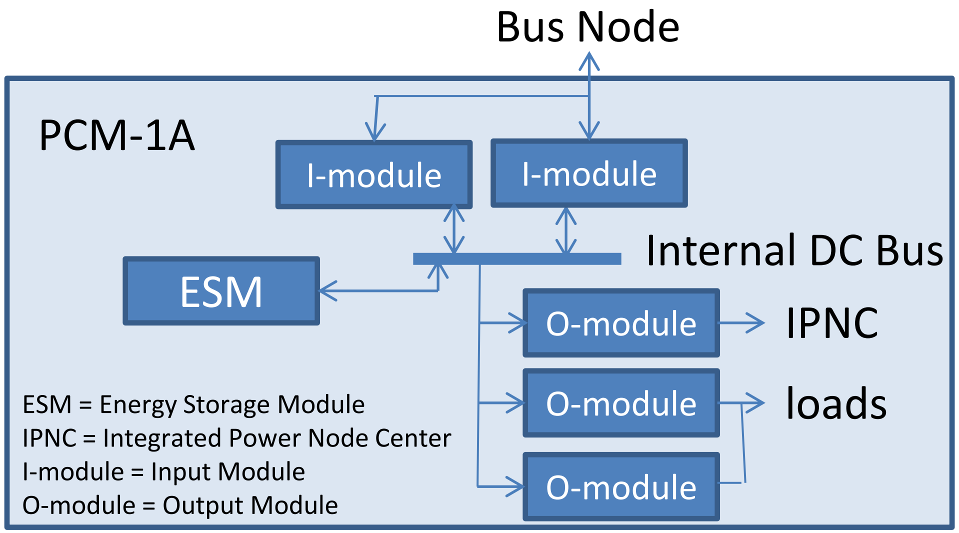
Propulsion Motor Modules

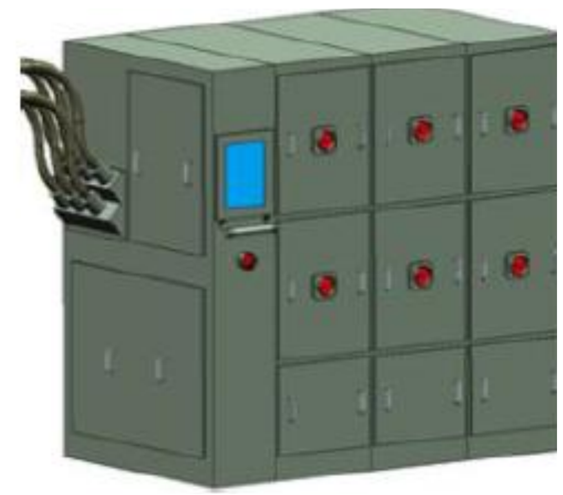
- Typically two motors for reliability
  - May share housing
- Normally powered by both MVDC busses
- Requires control interface for load management
- Consider contra-rotating propellers for fuel efficiency and minimizing installed electrical power generation capacity





PCM-1A / Energy





- Protects the MVDC bus from in-zone faults
- Provides hold up power while clearing faults on the MVDC Bus
- If desired, provides hold up power while standby generator starts
- If desired, contributes to energy storage for pulse power loads
- Provides conditioned power to loads
- Provides power to loads up to several MW (Lasers, Radars, Electronic Warfare)
- Provides power to “down-stream” power conversion (IPNC)
- Near term applications could use I-modules with AC inputs in “Energy Magazine” configuration

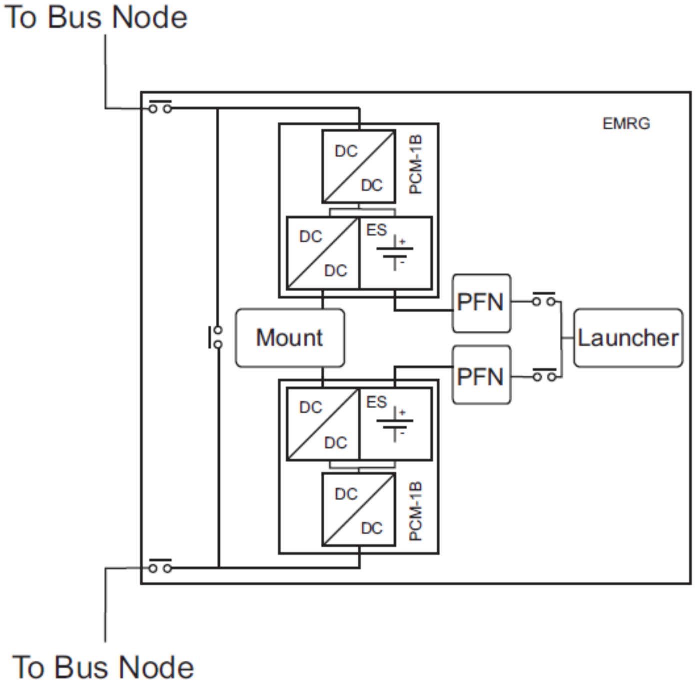
Integrated Power Node Center (IPNC)

- Update MIL-PRF-32272
  - Include 1000 VDC input modules
  - Include provision for energy storage for ~1 second
    - allow 450 VAC LCs in zone and in adjacent zone to reconfigure.
- Zone may have multiple IPNCs
- Supply
  - Un-interruptible loads
  - Supply loads with special power needs.
    - 400 Hz.
    - VSD motor loads
    - Perhaps Low voltage DC Loads

Courtesy L3

Notional Electromagnetic Railgun

- PCM-1B = Modular Power Conversion
  - 10's of MW
  - Powers Mount equipment in addition to Pulse Forming Networks (PFN)
- Normally powered by both MVDC busses
- Requires control interface for load management



Issues needing resolution

- Power Management
- Energy Storage / Energy Management
- System Stability
- Bus Regulation
- Prime Mover Regulation
- Fault Detection, Localization and Isolation
- System Grounding
- Magnetic Signature
- Affordability

Need resolution by 2025 to support 2030 Lead Ship Contract Award

Summary

- Power and energy density needs of a future destroyer with large pulse loads suggest a preference for MVDC
- An MVDC system must be affordable
- A number of technical issues need to be resolved in the next decade