Energy As A Weapon - Architecture Reloaded

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Synopsis

There has been a recent shift on ships power systems away from power management to energy management, due to the increasing use of Energy Storage fast acting power electronics convertors. This paper discusses the general shift in architecture to accommodate this, primarily to gain efficiency and resilience, covering items such as advanced AC and affordable DC networks, Shared, Centralised or Localised Energy Stores, Variable Speed generation, Energy Management vs Power Management. It also considers how to accommodate directed energy weapons on future and existing power systems in the Naval Arena. It outlines the broad options for efficiency and the supporting architectures without delving too much into the detail. Architecture reloaded, as we take a step back to evaluate the system solutions, to accommodate Energy, rather than Power as a weapon.

Keywords: Energy, DEW, Propulsion, Energy Storage AC, DC

1. Back to School, A few Definitions

As we know, the whole rationale of this series, is the engine as part of the weapon system.

Engine, comes from Middle English and old French as "ingine/engine" and from Latin "ingen", and was related to ingenuity, cunning. It moved into meaning large tool/weapon involving cunning, such as the medieval siege **engines**, and broadly came to mean turning energy from some form into kinetic energy. This suited steam engines, and then internal combustion engines, so is all about movement. So a device for creating movement, or kinetic energy from a different form of energy.

Power is Rate of change of energy, in joules per second. Now an important thing to note is that on normal electrical or mechanical systems, Power and Energy are seen as interchangeable, the engine is a 1MW engine, and we are running it at 790kW, therefore actually taking 790kJ per second, of a maximum possible 1MJ.

Energy is the Real Enabler, Energy is required to propel a ship, overcome friction, melt a missile in a DEW. Power is simply how fast the energy can be deployed.

Fuel is of course energy. Which we should measure it all in joules, but we are much more comfortable with gallons or litres, even though to get back to true energy we would need to multiply by energy density. Electrical Engineers invent other units for energy, kWh, as we feel happier multiplying power by time rather than just removing the time divisor. kWh actually has little to do with defining Power, or Hours precisely, it's really just total energy. We could express fuel as kWh, but we don't, because that is electrical energy, and fuel is mechanical energy so it's expressed in gallons. Our gas meters are therefore in cubic metres/volume, our electricity meters in kWh rather than what they all really should be which is joules.

Interestingly times are changing, and quite often gas is converted on the bill to kWh, so it can be compared to electrical power. Eventually perhaps this will converge to the SI units, joules.

2. Matching Power out to Power Generated Efficiently

The problem with equating power to energy for convenience, is that we often end up fitting engines based on peak loads, rather than average loads, not only that, but we rate engines for their duty, and also for spinning reserve, just in case there is an engine trip. This approach of peak rating, and spinning reserve results in large, heavy engine fits which are almost guaranteed not to run at their optimum operating point, which is often at 70-85% power. In many applications, they are run at less than half this level for resilience.

Designers of mechanical propulsion systems attempt to create efficiency by employing a fundamentally more fuel efficient engine. They have to live with the fuel curve of the engine, so they put up with a fuel curve that is poor at many normal operating points, such as loitering or cruising. The kW demand from the propulsor always comes from the engines connected to that propulsor. These systems are inflexible, but are simple, and as they do not convert power to electricity, they are the most efficient systems at full power, but ***only at full power***, as their fuel

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curve inefficiency at part load has significantly worse impact than the electrical power conversion losses for IEP. This leads to solutions such as the Complex Cycle Gas Turbine Engine development, which offered significant benefits at part load/speed fuel economy but at the expense of significant increases in mechanical complexity which impacted other areas. For Mechanical Propulsion Systems:

Shaft propulsor power kw(b) = propulsion engine power kw(b) &
Services load kw(e) = Services Generator Power kw(e)

Electrical propulsion systems designers can significantly help here, but it's interesting to understand why, the main advantage isn't only that they have a combined service and propulsion generation systems, it's the fact that they have decoupled individual propulsor power from individual generator power, so this means that they can share and optimise engine operating points to hit their sweet spots for fuel efficiency:

Total Propulsion Power kw(e) = Total Generated Power kw(e)

This is IEPs major advantage, any combination of engines can be matched to the load, actually of course you can include ship services power, which therefore yields the obvious:

Total Propulsion Power kW(e) +Total Services Power (e) = Total Generated Power kW(e)

Effectively the additional losses in the conversion to electrical energy kW(e) vs kW(b) are far outweighed by operation at better points on the fuel efficiency curve when engines can be switched off, i.e. at all speeds lower than maximum. Even electrical propulsion suppliers will admit that they cannot match the mechanical efficiency at full/rated load. This is why vessels that only have one speed or duty cycle, are rarely electric.

Hybrid PTO/PTI propulsion systems are somewhere in between. If you turn off the mechanical propulsion engine, then they are effectively full electric systems, at reduced powers for cruising. They turn off the thirsty sprint engines to run efficiently if they are PTI (Power Take In)/Motoring. In PTI mode, they are partially rated full electric propulsion systems.

PTI Mode: Total Motor Propulsion Power kW(e) + Total Services Power(e) = Total Generated Power kW(e)

PTO Mode: Shaft Propulsion Power kW(b) + Shaft Generator Power kW(e) = Sprint Engine power kW(e)
&
Services Load kW(e) = Services Generator Power kW(e) + Shaft Generator Power k(e)

In PTO mode, hybrids are effectively mechanical propulsion systems which attempt to load the propulsion engines to a more efficient fuel operating point by adding service load. Hybrid systems are always mechanically and configuration wise, more complicated than full electrical systems, as essentially, they change state between mechanical systems with a shaft generator at full power to small full electrical systems at cruising speed.

All of these solutions, mechanical, electrical or hybrid are all about matching instantaneous power generation to Instantaneous Consumption Efficiently. They are constrained by either the generator engine operating speed or the engine fuel curve at a particular operating point. All of these are maintaining power in = power out. Techniques like stopping engines, effectively *derates the whole system* to match demand, to hit the SFC sweet spot, this is IEPs advantage.

Another approach, for mechanical or PTO, if you have a variable pitch propeller is to try to adjust the relationship between speed and power on the engine, to pick the best combination of engine speed and load to pick a sweet spot on the engine fuel curve. Instead of changing the number of engines on line, change the engines operating speed whilst maintaining load.

This can also be done with electrical systems, with a Fixed Pitch Propeller, but you have to vary the generator frequency, which to some electrical engineers would seem to not be possible, it is very possible, and particularly suits IEP systems, and also, can be equally applied to AC and DC systems.

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Slowing down generator engines, is effectively derating the whole power system to change the fuel efficiency curve, whilst maintaining the power. This is another advantage of electric over mechanical, you can slow the engine but maintain the power, to hit a greater efficiency. It's the electrical equivalent of CPP.

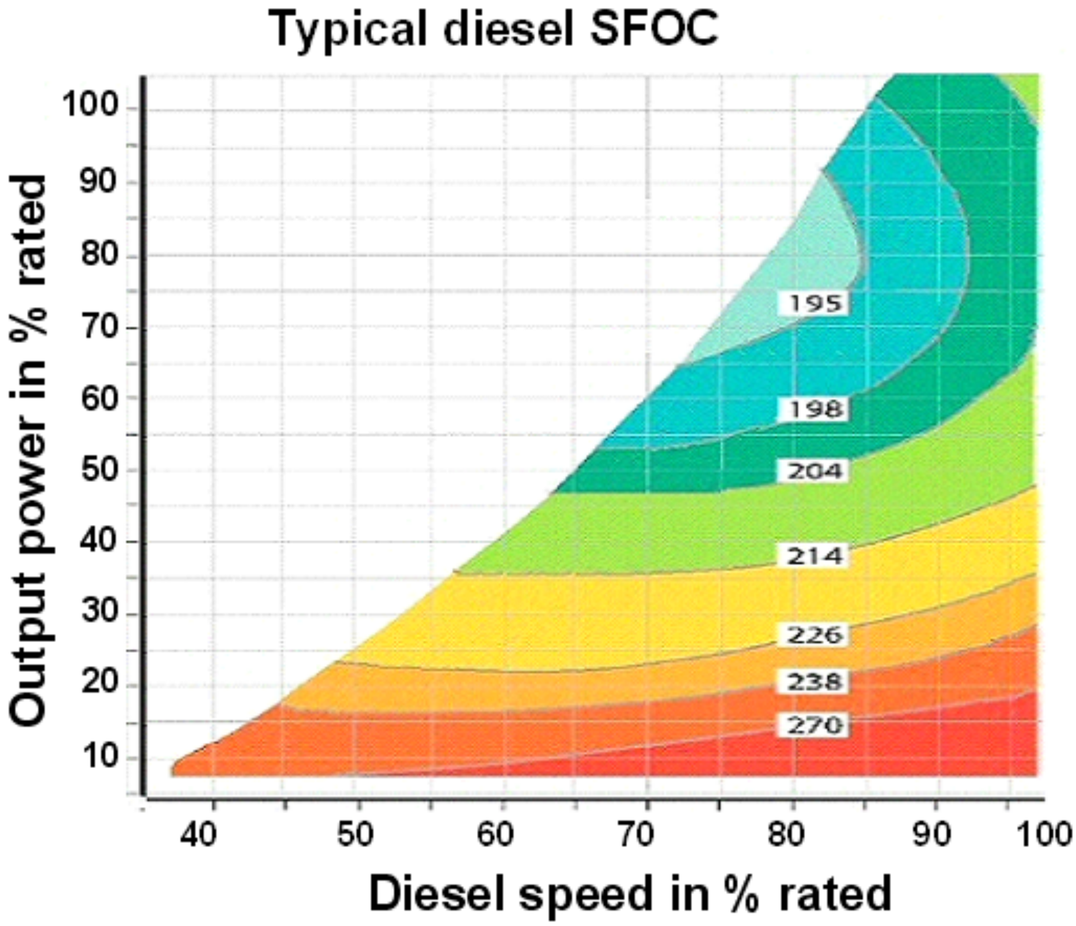

Fig.1 - Typical Diesel SFOC varying power and speed together

The curve in Fig.1 illustrates this, it is a graph of engine speed vs output power, Hz vs kW for a generator, where the coloured bands represent specific fuel consumption, from the worst in red, to the best in blue. If you drop the engine speed from 100 to 80%, whilst maintaining 80% load, you go from the dark green to the light blue, and become more efficient, due to less rotational losses, this is effectively a temporary derate, so load acceptance and max power is affected until the engine speeds up again.

All of these techniques are trying to match kW in from kW out exactly and reduce losses and run at the optimal point on an engine curve. This is all about power conversion, not energy conversion. What if instantaneous use of the power generator was not a constraint? As it is with all of the above efficiency considerations. The real game changer is the application of energy storage. This allows the unity relationship between kW generated and kW consumed to be broken. The engines can now provide more or less energy at any one instant than that demanded by the load. We can now consider energy different to power.

3. Energy Management

The power management system now has to become an Energy Management System. Energy storage and management is like a huge adrenalin injection into the arm for Electrical Systems, as it now effectively allows engines to run as long-term RMS energy sources, rather than short term kW providers. Depending on the energy storage capacity.

This opens up a huge number of possibilities:

- Load levelling/dynamic support/peak shaving inc. accommodating Directed Energy Weapons (DEW)
- Fast acceleration at propulsors, but ramped acceleration on engines
- Single or reduced generator operation, as spinning reserve is no longer required, it can now be static.
- UPS functionality for the power system, preventing TLFs.
- Real reduction in engine run hours
- Avoidance of wasted fuel and higher emissions during impact loading
- Ability to run in harbour with no shore supply or harbour engine
- Hybrid boost, where Estore cyclically charges/discharges to allow engine to be stopped 50% of the time

4. Centralised vs Localised

In the original electric ship concept, this was the Zonal Power Supply Unit (ZPSU) vs Bulk Energy Storage System (BESS) debate, If you choose local, you can only practically support local downstream loads, and you need local power conversion to do it. It addresses ride through, but not so many of the other benefits, and is more difficult to share around the ship. Local stores are also considerably more expensive per kWh. compared to centralised energy stores, perhaps one per bus, which are currently the real growth area in marine, they are more like static prime movers rather than local UPS supplies. This centralised store, gives both economy of scale and maximum flexibility.

5. Accommodating DE Weapons and High Impact Loads

Current DEWs seem to be in the sub 1MW range of useful power, for a >45 MW IEP system such as Type 45 or QEC, with more than minimal prime movers running, this sort of impact load is not significant even without energy storage fitted. 1MW pulse is less than 1% load step on the QEC Power System. Not so for Hybrid, if we took a ship services system of say 5MW, then a 1MW load would represent 20% step load, and whilst it may take it, there is precious little room for growth and emissions and engine wear would be high, which makes energy storage an almost certain requirement for almost any size of DEW on a hybrid system. On the LV bus, rather than local to the gun would also be more advantageous.

What about when the gun gets bigger? If you don't have energy storage, you have to hope you are running on electric motors at some load if you have a hybrid.

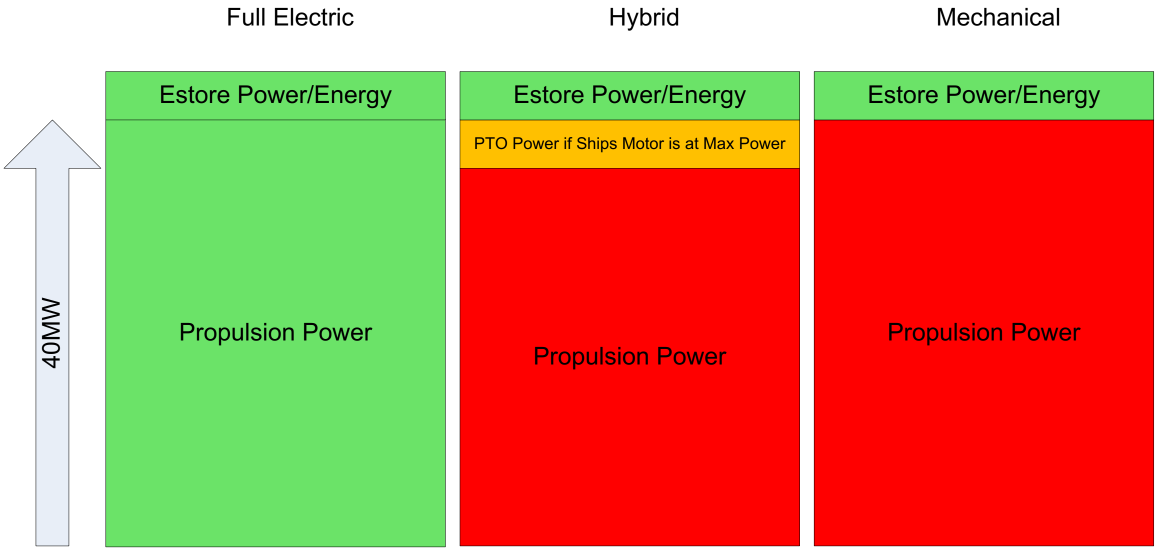

Fig.2 – Scaled Instantaneous Power/Energy Available for DEW on a Destroyer

For a long time, we have talked of engine as a weapon, electric propulsion, without actually saying how the energy would be instantly shared. Without energy storage, only the propulsion converter is really fast enough to match the gun. So the trick would be to load step off the propulsion motor in antiphase to the gun if the motor was running, both for IEP and Hybrid. Gun asks for 10MW, propulsion converter drops 10MW, but remains synchronised with its rotor. When the gunfire is over, the gun passes load back instantly to the motor. Prime movers see no changes in load. The engine is the *RMS weapon*, but the instantaneous switching of energy between propulsion drive and DEW convertors is the key. Effectively whatever the current hybrid or IEP electric propulsion load is, it can be instantaneously traded for weapon power, with no impact on the prime movers. If the weapon or load demanded more than the current propulsion load, then the remainder would have to be taken up by the engine response or provided by energy storage.

Not all systems are created equal. Fig.2 shows scaled comparison. The green colour is potential instantaneous electrical power that is available to an impact load such as a DEW. Red is unusable prime mover power. IEP without energy storage, if running could accept a propulsion convertor/DEW converter trade of 40MW, with no impact on prime movers. IEP also has a 40MW power system to drop on the DEW load step if the propulsion is stationary (services are ignored in all cases as they need to be maintained on all options). Hybrid is much worse, it can contribute say 5MW from propulsion if it was running, if it wasn't, it's no better than mechanical. Remember you are already using the service load so you can't drop 5MW extra, you have neither the kW or the engine response. Not much difference between Hybrid and Mechanical here, Mechanical never has the kW or engine response for a large load step. None of this includes additional contributions such as regenerating IEP and Hybrid to take out energy from the ship by slowing down, this is possible but of limited benefit compared with the power system installed kW.

Energy store could be applied to all three, but it's an expensive way to prop up a legacy power system that's too small. Also, when you get beyond a few MW, it's really too big a load for 440V. 690V helps on a hybrid, but not much. So, Energy storage is the enabler here. It can stand in when you are loitering, and it can make the whole process more secure. In fact, drilling rigs have employed energy stores for some time, at the few MW scale, as they have cyclic power of up to a million cycles a year, and currently much more power than the current DEW weapons. It really is saying if you haven't installed the power, you can still get the energy, with a storage device, but it's a more expensive option for higher powers on low rated power system.

6. Retrofittable Energy Stores

There is a growing demand in commercial marine for self-contained power packs, fitted in ISO containers, to provide permanent or temporary addition of energy store to electric vessels. The ISO container is far from a battery, it's a whole self-contained static prime mover, with Battery, Convertor, Cooling, Firefighting and control all within the unit. The only connection is a three-phase cable to the 690/440V supply, and especially if the ship has a shore supply point, the unit can be fitted in hours.

Fig.3 Self Contained Retrofittable Deck Mounted Energy Stores

To get the most features, there needs to be modifications to transform the Power Management system into an Energy Management System, but it can be also be fitted autonomously to provide UPS, TLF prevention and Load Levelling.

Commercial customers are, and perhaps the MoD should consider trialling such a unit on various legacy platforms. These could be temporarily accommodated in the hangar or flight deck, and rapidly used to show the real benefits of energy storage without any need to refit, and also could supplement a failed engine, or support DEW trials temporarily on board a ship.

7. AC vs Advanced AC vs DC

Having discussed IEP and hybrid, variable frequency prime movers and energy storage to manage energy and efficiency, there is often a lot of discussion about the architectures, voltages and frequencies that can accommodate such features easily into the systems. I will touch on a comparison of the different approaches here and the fact that all features can be accommodated on both AC and DC architectures with equal simplicity/difficulty.

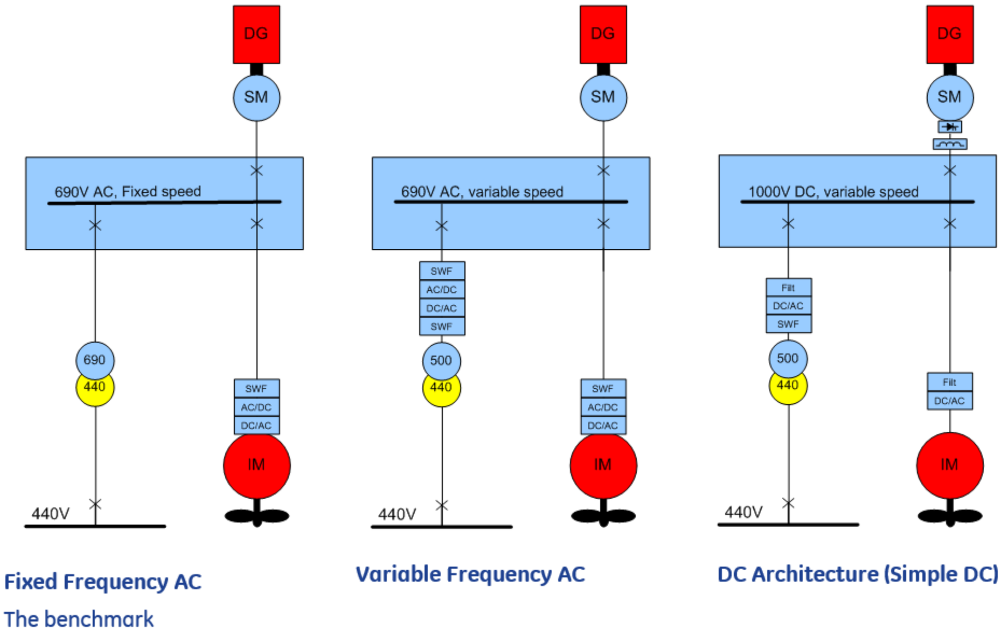

Fig.4 - Building Blocks of fixed AC, Variable AC and DC

If we really simplify it, we can consider three main architectures summarised in Fig.4, fixed AC, Variable Frequency AC, and DC. Commercial drives can all now be transformerless, up to 11KV, so no transformers, and no harmonic filters required. For advanced AC, we need a convertor to convert either the variable AC or DC back to 440V ship services. For the Advanced AC and DC, we are really moving around bridges, Generators are AC, motors are AC, so on the DC we simply move the bridge from the drive to the generator, and distribute at DC, instead of distributing at AC. In effect, we stretch the DC link in the drive to be the whole distribution. You have to balance different and exotic solid-state switchgear with potential EMC benefits. There are also many magnitudes more suppliers of AC distribution, than DC especially at high powers.

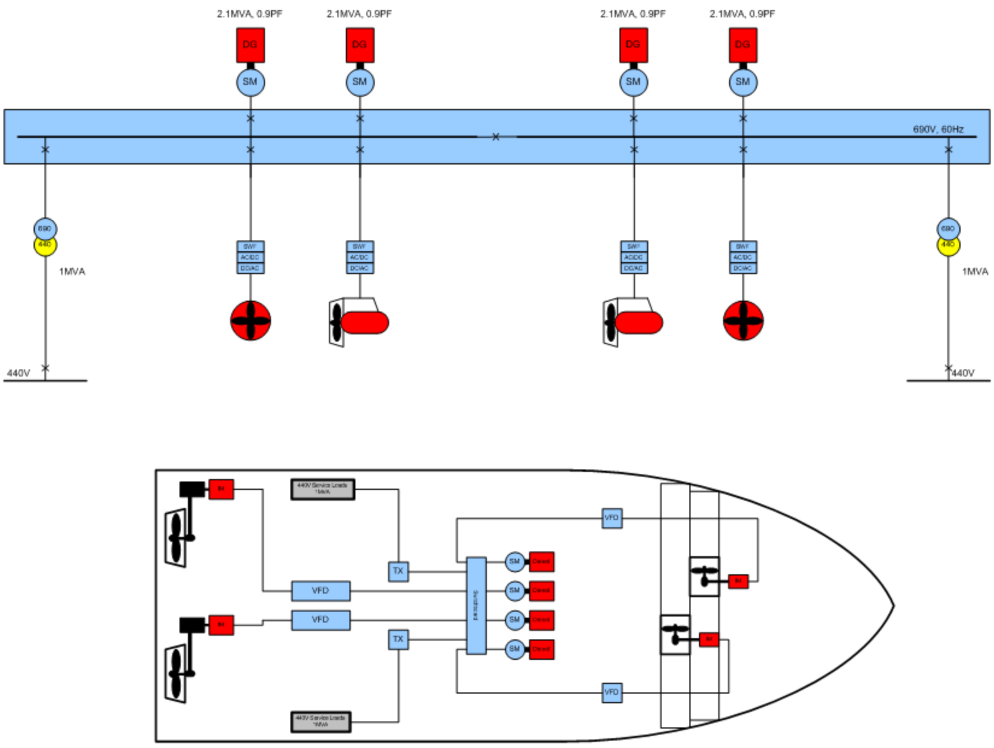

Fig.5 - Reference Fixed AC System Architecture

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Fig. 5 shows a classical AC system on a standard ship, an OSSV supply vessel, but it equally applies to all sectors, fixed generation frequency, AC distribution, transformers from generation voltage to services. It does have Active front end drives, so no need for transformers, or harmonic filters.

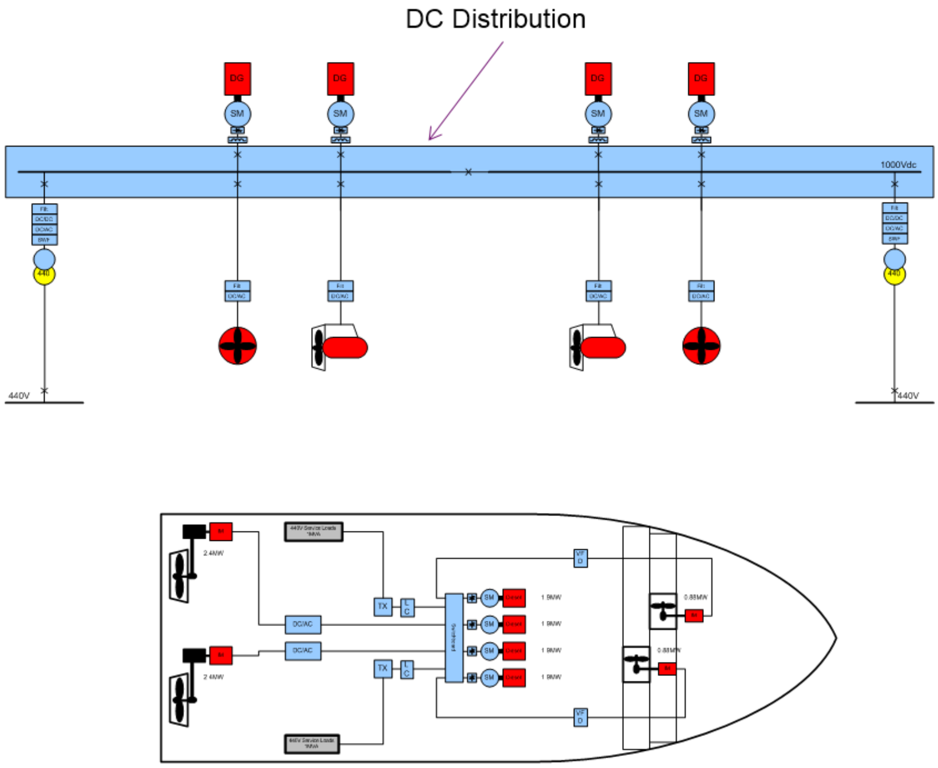

Fig.6 - Reference DC Architecture

Fig.6 shows a DC system, the generators have convertors, a link convertor is needed to produce ship services voltages, there is only an inverting bridge on the drives, as the convertor bridge has moved to the generators. There is a distribution challenge, as it's now DC, and either fuses or expensive convertor solid state breakers are required. It's interesting to note that the small DC systems are often clustered into a few switchboards, and fuses applied to reduce the cost and risk of solid-state breakers. This can have vulnerability consequences for single point of failure, loss of switchboard if not handled carefully. It's interesting to note that if fuses are allowed in DC, they should be allowed in AC in similar duties.

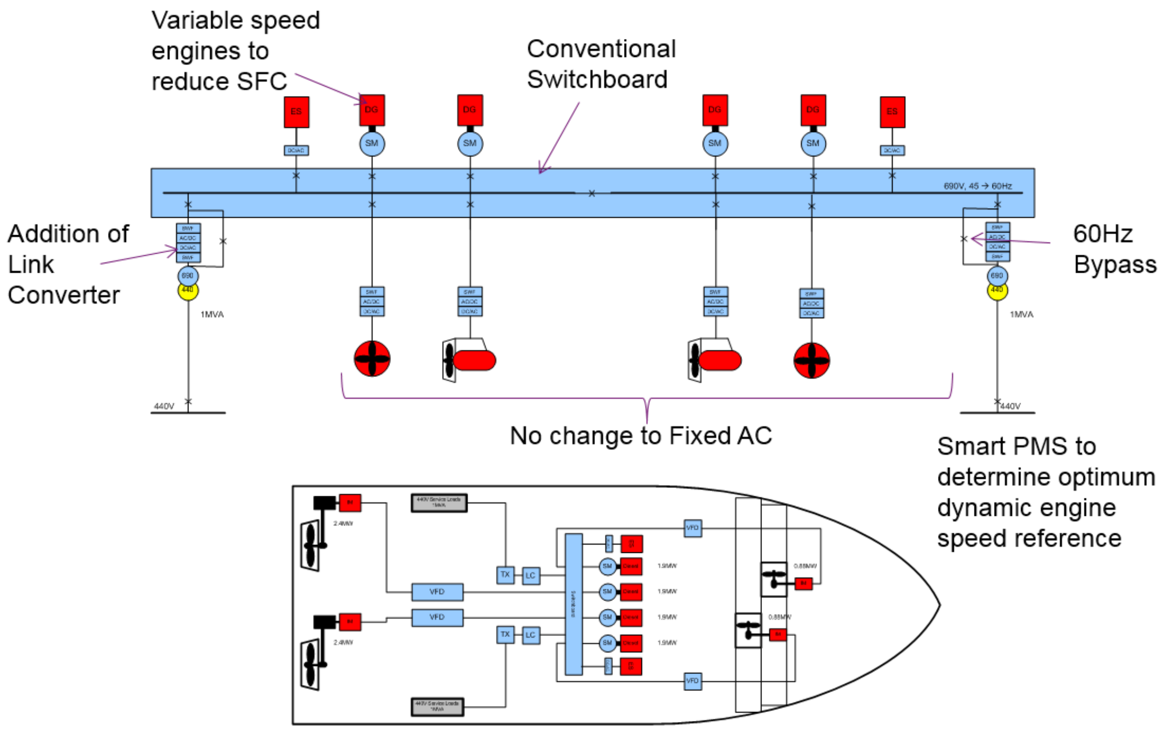

Fig.7 - Reference Advanced AC Architecture

Fig.7 shows an advanced AC system, with energy storage and variable frequency bus, but still with classical distribution. There is a link convertor to the LV, but this can be bypassed if there is a problem and the system operated at 60Hz. Energy storage is shown, and of course this can be added to the other two systems also. All of the energy stores in practice require an interface convertor as it is just not viable to vary the bus voltage to match the terminal volts of the battery, even on DC systems unless it's an application like a submarine, where the whole system is dominated by the battery.

Advantages that Advanced AC shares with the DC Systems:

- Transformerless
- No Harmonic Filters
- Same Energy Store
- Isolation of QPS via a link convertor
- Variation of generator power factor, including Unity Power Factor operation if tolerable
- Variable frequency generation for efficiency (if required).
- Single Bus Operation with Generator Advanced Protection
- Single Prime Mover operation with Energy Store Backup

Advantages of Advanced AC Advantages over DC

- Widely available Switchgear Technology, protection and cabling.
- Can revert to Transformer Fed with Bypass and 60Hz if required.
- Can operate whole generation system and services without Power Electronics if required.

Advantages of DC over Advanced AC

- Fast Synchronising

DC systems are making their way onto ships at smaller scales but there are compromises, often to limit breaker costs and difficulties in cable/distribution they become centralised into a single or two large switchboards, with generator, drive and ship services bridges all suited together. This creates large centralised complex switchboards where equipment is harder to subdivide, and careful attention would have to be paid to naval applications where redundancy, graceful degradation and survivability are paramount. Greater survivability is often achieved by more redundancy groups, or more dispersal of distribution rather than centralisation. It is also interesting to note that such centralisation of equipment and replacement of breakers with fuses seems to be more acceptable on DC than AC systems to aid their adoption, despite the negative consequences.

8. The Fuel Line

There are therefore many techniques to make electrical propulsion systems efficient, with OPEX and CAPEX impacts shown in Fig.8. which represents a fuel line, the more to the left, the more efficient and the less fuel used. Green is OPEX fuel benefit where blue is CAPEX cost. Yellow is other OPEX considerations.

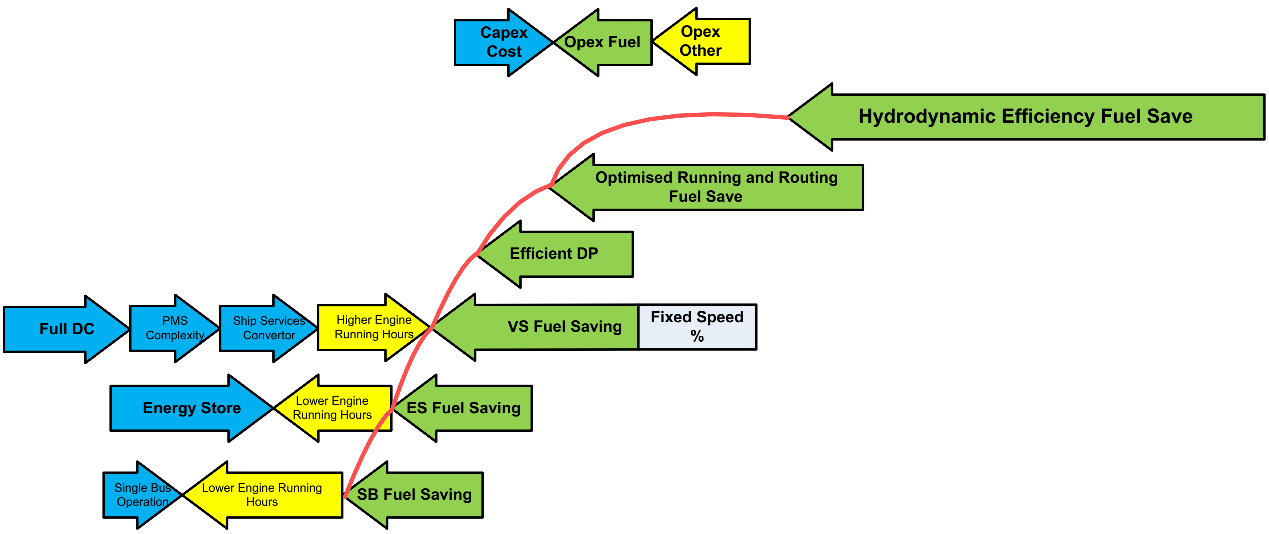

Fig.8 - The Fuel Efficiency Line

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The line represents savings for an Electric Propulsion system depending on features selected, irrespective of whether its AC or DC, and also seeks to show that many of these techniques overlap, so they do not give mutually exclusive savings, it is therefore for the engineer to analyse and pick the best features and cost benefit analysis to suit a particular application. The top two are still perhaps most important, get an efficient Hull and Hydrodynamics and pick a flexible set of prime movers and operate them efficiently. Use Efficient Dynamic Positioning that balances accurate positioning with minimal thruster operation. Then variable speed fuel saving can be fitted, but it requires power management system modifications, and either a DC system or an advanced AC system, also remember there will be a portion of time when the system will run at fixed frequency as the most efficient point anyway. A consequence can also be that reduced engine powers can increase engine running hours, and at lower speeds, which needs to be considered for maintenance. Energy store is next and this has a direct cost of the batteries and converter but has the additional OPEX benefit of reduced running hours due to it acting as static spinning reserve. The final item on the line is operation as a single bus, even during resilient modes, which requires some protection changes, but saves both fuel and engine running hours.

Good designers naturally seek hydrodynamic savings, and should pick best fit prime movers, to minimise large steps in configurable generators. Efficient DP is also fitted in modern systems, so really variable frequency bus, energy storage and single bus operation are considered as optional enhancements, and whilst rarely all fitted, single bus operation is probably the most popular, needing only protection changes, followed by Energy storage, and then perhaps variable speed engines. These lower options overlap in terms of engine hour running and fuel saving benefits. Energy storage increases in popularity due to not only fuel saving, but emissions, resilience and Engine Running hour benefits.

9. Conclusion

All of the efficiency saving techniques are rarely all fitted to a single system, because their savings are not mutually exclusive. Also, they equally apply to AC and DC, it's not the architecture that's so important here, it's how to accommodate and integrate the efficiency techniques. Some combinations are however pulling ahead, items such as Energy Storage and Single bus are becoming more widespread, even on retrofit workhorse vessels. It's a compelling combination as running prime movers gives less resilience and more efficiency, and energy store replaces the resilience.

Navy systems have always been resilient, with Efficiency, until hybrid electric or IEP, being somewhat secondary, but now the systems can have an Efficiency or Resilient "Reconfiguration" depending on the threat level. Commercial marine, especially the oil industry requires resilience and efficiency simultaneously and are working hard towards it with Single Bus Operation, Reduced Prime Movers and Impact Loading like Drilling covered by energy storage. Don't underestimate the consequences of a TLF on an oil vessel, can cause multibillion pound impact like Deepwater horizon, but they also need to be efficient 24/7 in the danger zone, and they need to Shoot….I mean drill with high energy impulses.

The addition of energy storage changes the system to be all about Energy Management and energy control, and for high impact loads such as weapon systems, only convertors are fast enough to do this, whether it's a battery convertor on the EStore propping up a weak hybrid, or a propulsion convertor diverting power from a propulsion drive on IEP, the energy management system and the ability to react at power electronic speed are the key. The energy storage benefits are so compelling that the market is retrofitting them with minimal invasive changes on commercial vessels, in fact they may even be fitted and removed depending on the mission/charter.

Don't look to your engines, even if they have spinning reserve headroom, even if they could take the impact, they would be inefficiently doing it, and have high impacts on quality of power supply and high impacts on maintenance. Store, Manage and Divert the System Energy, do not try to manage the instantaneous generator power. The Engine is not a weapon, the RMS Energy it produces is.