Automated propulsion and generation flexibility for strategic naval warfare advantages

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Synopsis

This paper describes various propulsion system options for Hybrid and Integrated Full Electric Propulsion (IFEP) arrangements. It describes ongoing electrical power density and recharge frequency challenges which navies and their engineers face with the development of future weapon systems (DEWs; lasers, rail guns) and aircraft launch systems (EMALS; electromagnetic catapults). It also explains advantages which vast national and localised (island mode) electrical grids have found by multi-tasking flywheel motor / generators by adding a simple automatic clutch mechanism. The paper draws comparisons between naval and terrestrial power generation systems, concluding how such commonality could lead to improved on-board energy distribution and therefore also weapon performance.

Keywords: Propulsion; Hybrid; IFEP; Power Generation; Directed Energy Weapons; Flywheels; Survivability; Flexibility; Redundancy; Automation

1. Introduction:

Debate between Integrated Full Electrical Electric Propulsion (IFEP) and HYBRID mechanical propulsion systems continues in other publications. This paper has not been written to continue that argument but to instead properly consider all machinery options for both.

Propulsion clutches have excellent experience within naval propulsion systems, allowing engine and subsystem multi-tasking, thereby reducing marine architecture space and weight. The minutiae of each clutch design creates operability advantages and disadvantages. Auxiliary systems required (or not) by each design, create further cost, space, weight and maintenance advantages.

Overrunning clutches are also well established within terrestrial generations systems. Research conducted by SSS Gears (SSS Clutches) shows that marine engineers and technology disruptors within the same workspace need to become better informed of the reasoning.

Events concluding with powerless warships are well documented. Lessons learned from the Iberian electrical grid failure (May 2025) are ongoing at time of this paper's publication and similar events occurred in South Australia in 2016 and the UK in August 2019. Solutions added to terrestrial power grids enabling multi-tasking or "revenue stacking", should therefore be properly considered by marine propulsion and electrical distribution engineers.

Terrestrial distribution grids span larger areas than a warship, but the future power challenges created by Direct Energy Weapons (DEWs) requires that warships become highly power dense. Military agencies are examining the electrical "ride through" advantages which kinetic energy and electrical inertia, produced by electro-mechanical flywheels, can bring to DEWs. Terrestrial grids have already added clutches to generator systems in both national and "islanded" grids for the same reasons.

Considering different ways to use these engines as a weapon within naval system is therefore an opportunity for each engine's subsystem and this paper shares references of land and marine power generation applications.

2. Hybrid Propulsion

Hybrid propulsion propels a ship using a combination of mechanical and electrical prime movers as illustrated in Figure 1. Electric motors normally provide cruise speed, and either a gas turbine or diesel engine are “clutched in” to sprint.

Combinations of each, separated by watertight bulkheads, cover redundancy and survivability measures, in addition to providing their key requirement to propel the ship as efficiently at cruise and sprint, through one or two propulsors. “OR”, alternatively “AND” machinery combinations are possible, thus the initialism “CODELOG” etc. outlined within the glossary of terms. Emergency propulsion can be provided by retractable devices.

As with all propulsive effort, power and speed are related by cube law, thus the most power dense and fuel efficient machinery is of key importance to propulsion system integrators (PSIs). Efficient machinery combination is most often achieved by main reduction gears (MRG), clutches and fluid couplings whose efficiency is of equal importance to PSIs.

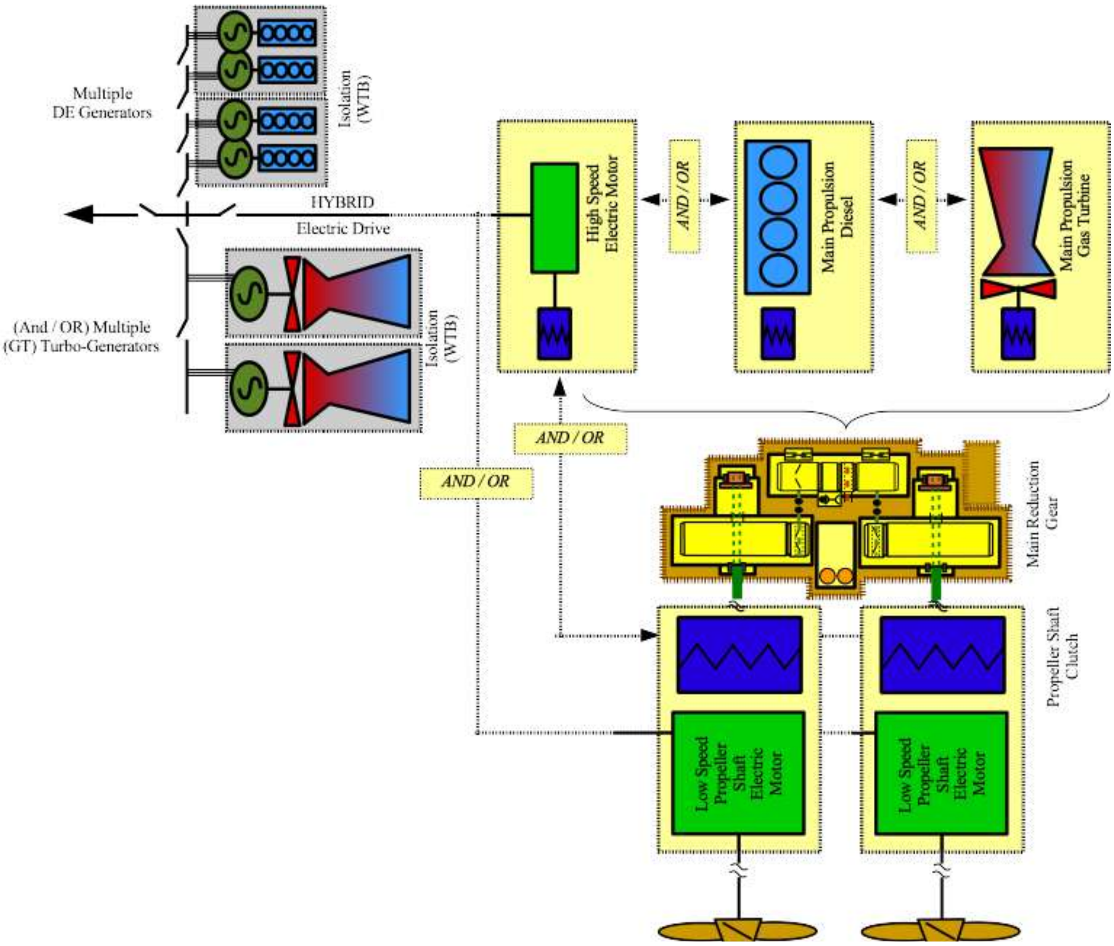


Figure 1: Illustration of Hybrid Electric Drive Propulsion

2.1 Electrical Generation for Hybrid Propulsion

IFEP and hybrid electrical generation are similar and described within IFEP section 5.

2.2 Mechanical Propulsion within Hybrid Propulsion

Hybrid drive clutches illustrated above can be subcategorised:

2.2.1 Propeller Shaft Clutches

These clutches disconnect the main reduction gear of the sprint drive prime mover. This concept was first used in a hybrid platform on the Type 23 frigate, to remove the prevalent MRG noise whilst operating in cruise (EM) drive, conducive for towed array sonar efficacy during ASW operation. Careful clutch choice must consider:

i. Robust performance, proven by reference; failure can disable an entire propulsion shaft.
ii. Overall cost, considering additional auxiliary systems necessitating clutch operation.
iii. Operating cost / risk, including parasitic losses within auxiliary systems.

Points ii) and iii) must consider noise, weight, space and maintenance requirements.

Section 3 outlines hidden advantages of some clutch designs which self-lubricate and self-cool in EM / ASW mode, reducing dependence on auxiliary systems.

2.2.2 Gas Turbine Disconnect Clutches

Primary Pinion Clutches disconnect the prime mover from its main reduction gear. Whilst it might seem superfluous to include a clutch in this position, if a propeller shaft clutch is also used, there are three major benefits to gas turbine isolation:

- Simplifying GT commissioning, without having to operating MRG.
- MRG isolation for GT tests and adjustments (fuel valve calibration, overspeed trip testing, turbine water wash / clean).
- Isolate GT power turbine from MRG inertia when sprint drive power is reduced. This ensures that MRG inertia cannot back-drive the GT power turbine, which risks GT stall / flame out.

3 **Clutch Options**

Various propulsion clutch options exist, each with unique advantages and otherwise. As is the key with any system, the bigger overall picture is often less obvious

3.1 *Friction Plate Clutches*

Friction plate clutches are engaged via axial pressure in the form of a spring or hydraulic servos, pressing a series of plates together to connect driving and driven machines. Above a certain torque / speed rating, the friction load transmitted by the plates becomes too large for the “dry plate” arrangement used within many automobiles and a wet, or oil lubricated, type is instead necessary.

Their advantages are mainly related to simplicity to understand and low cost. Disadvantages include the following illustrated in Figure 2:

a. Requirement to add complicated monitoring and control systems to govern engagement and disengagement.
b. Plate wear, leading to particulate contamination which in the case of wet plate types requires separate lubrication systems when installed within reduction gears.
c. Limited power and operating speed compared with other designs.
d. High-pressure auxiliary oil system required for wet plate operation.
e. Low-pressure auxiliary oil system required for wet plate lubrication and cooling.
f. Weight, space, naval architecture design constraints and maintenance costs / risk arising from points a to e.

(Bos 2018, Hendry et al 2019 & 2020)

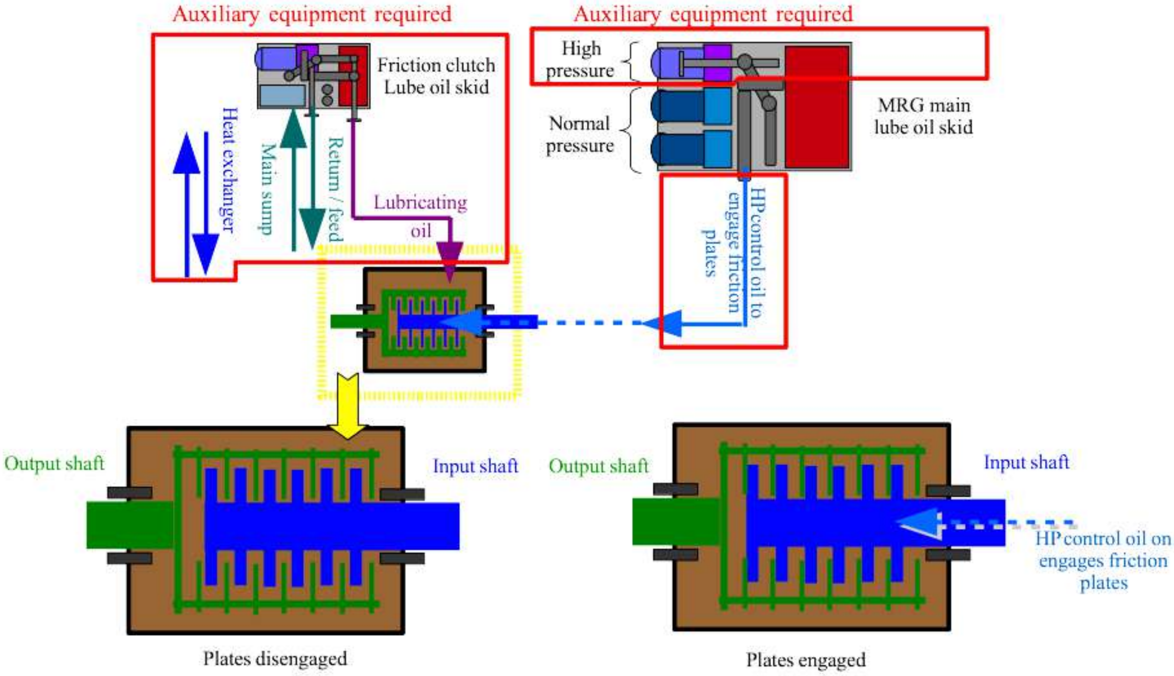


Figure 2: Friction Clutch Illustration

The complication caused by a combination of these disadvantages, leading to control system errors, has rendered naval warships powerless as recently as 2016 ("Damaged clutch shut down new Navy warship", Lendon + Cohen, CNN)

3.2 *Sprag, Cam or Roller Clutches*

Roller clutches can be considered simply as one-way bearings which will overrun in one relative direction of rotation, or lock up and transmit torque in the other relative direction. Sprag or cam clutches are similar to roller types, although the rollers and their associated ramps are replaced by sprags or cams, carried within a driving member which lock into engagement with a driven member.

Their advantages these clutch types are simplicity of construction and therefore reduced cost and weight. Their disadvantages relate to their torque transmission being via line contact between the roller and driven member as illustrated in Figure 3. Whilst sprag and cam clutch mating surfaces are curved, thus reducing surface / contact pressure, all such engaging mechanisms also transmit the torque. The number of engagements endured, the relative engagement rate, or acceleration, of the driving and driven machinery as well as its inertia therefore have an impact on product life.

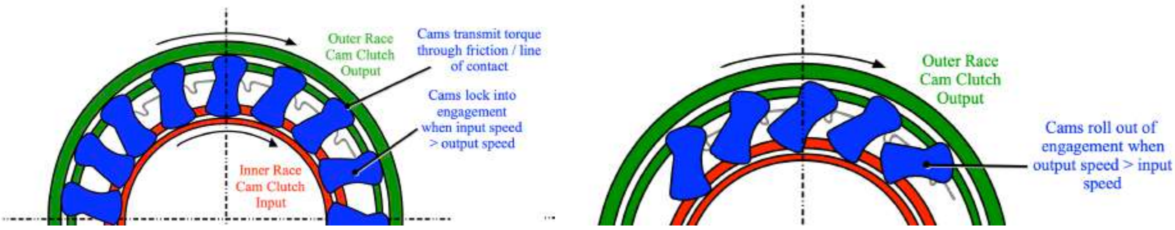


Figure 3: Cam Clutch Illustration

3.3 *Gear Type Overrunning Clutches with Mechanical Baulked Protection*

Gear type overrunning clutches can be considered simply as a pawl and ratchet mechanism, which moves a sliding component along a helical spline, enabling engagement of a gear coupling as illustrated below at Figure 4a. The gear coupling then transmits the driving machine torque to the driven machine, once the teeth are meshed and the sliding component reaches its end stop. The fundamental advantage over former designs discussed is that the engagement mechanism does not transmit torque. Torque is instead transmitted through a gear tooth mesh.

Disengagement occurs when the torque reaction reverses, thus the engagement and disengagement is completely mechanical and automated, removing the requirement for complicated control systems.

3.3.1 *Additional Design Features of SSS Clutches for Strategic Operating Advantages*

SSS Clutches in particular have increased the functionality of this design by including the following:

a. Dashpot - cushions engagement and disengagement inertia.
b. Lock out – selectively disables clutch engagement, enabling FPP AFT propulsion, without back driving unidirectional machinery. This feature also significantly reduces the "drag" associated with competing designs, which instead require large oil flows (and cooling), thus SSS Clutches reduce power loss and in turn reduce platform noise.
c. Baulk mechanism – mechanical protection against machinery damage, if transition between operating modes is inadvertently selected at a functionally inappropriate time.
d. Self-lubricating mechanism for LOCKED OUT mode, enabling auxiliary lubrication systems to be shut down.

These design features contribute significantly to how a warship platform can operate with a strategic naval warfare advantage.

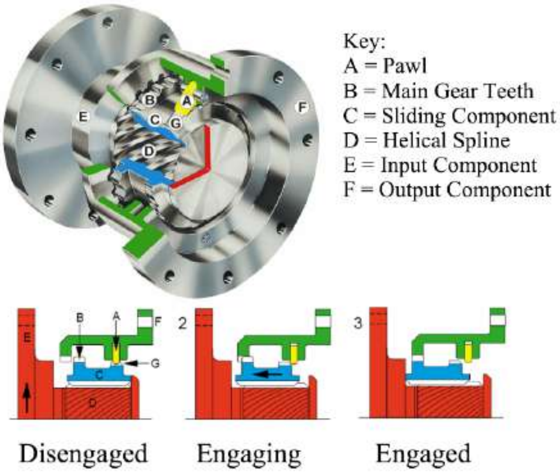


Figure 4a: SSS Clutch basic function

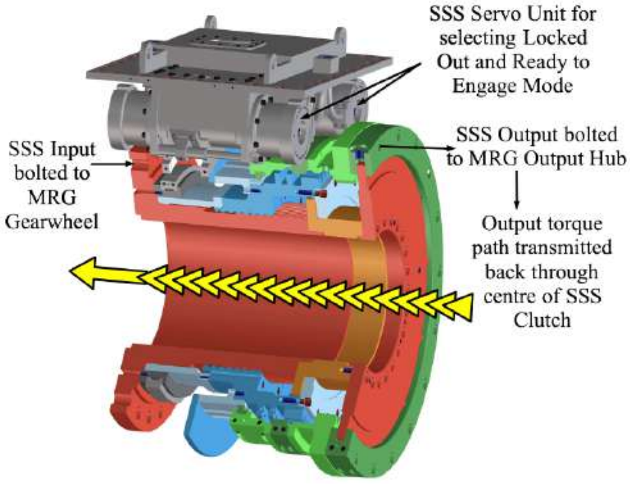


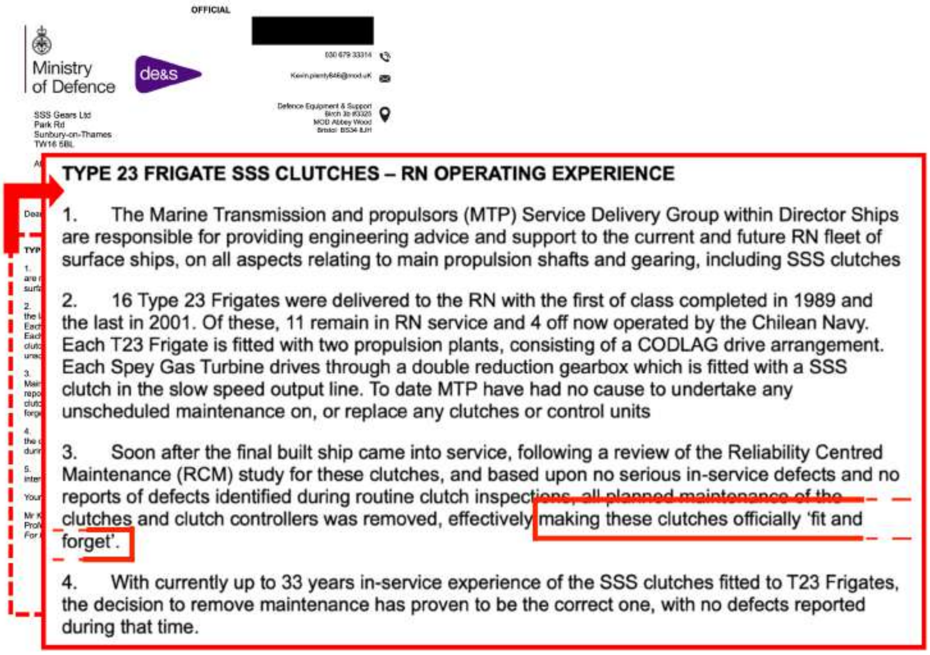
Figure 4b: Size 360T SSS Clutch with Servo Driven Baulk Protected Lockout Mechanism

One key disadvantage of gear type overrunning clutches is misconception over capital cost (CAPEX). Whilst an additional cost is incurred by achieving the advantages listed a) - d) above, propulsion system integrators occasionally overlook, misunderstand or have insufficient time to properly compare the reduced cost, space and weight which these gear type overrunning clutches save over competing designs (sections 3.1 and 3.2).

Increased time on station as a direct result of improved efficiency of gear type clutches must also be considered in addition to fuel cost. Former papers publish figures detailing these savings (Bos 2018 & Hendry et al 2019, 2020):

- US$ 40-250 million fuel saving.
- 10,000 kg (gross) platform weight saving.
- 30 m^2 platform space.
- 4,900 – 9,800 kg auxiliary equipment weight saving.
- Service, maintenance and training thereof of associated equipment unnecessary.

These advantages neatly summarise why SSS Clutches continue to be rated as “Fit and Forget” equipment by UK MOD (DE&S):



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TYPE 23 FRIGATE SSS CLUTCHES – RN OPERATING EXPERIENCE

1. The Marine Transmission and propulsors (MTP) Service Delivery Group within Director Ships are responsible for providing engineering advice and support to the current and future RN fleet of surface ships, on all aspects relating to main propulsion shafts and gearing, including SSS clutches

2. 16 Type 23 Frigates were delivered to the RN with the first of class completed in 1989 and the last in 2001. Of these, 11 remain in RN service and 4 off now operated by the Chilean Navy. Each T23 Frigate is fitted with two propulsion plants, consisting of a CODLAG drive arrangement. Each Spey Gas Turbine drives through a double reduction gearbox which is fitted with a SSS clutch in the slow speed output line. To date MTP have had no cause to undertake any unscheduled maintenance on, or replace any clutches or control units

3. Soon after the final built ship came into service, following a review of the Reliability Centred Maintenance (RCM) study for these clutches, and based upon no serious in-service defects and no reports of defects identified during routine clutch inspections, all planned maintenance of the clutches and clutch controllers was removed, effectively making these clutches officially ‘fit and forget’.

4. With currently up to 33 years in-service experience of the SSS clutches fitted to T23 Frigates, the decision to remove maintenance has proven to be the correct one, with no defects reported during that time.

Figure 5: MOD DE&S “Fit and Forget” Letter

The US Navy is the largest single end user of SSS Clutches at >1,500 installed references, with a published MTBF rating >270,000 operating hours across all platforms studied. Of note is that “failures” were all attributed to outside events not attributable to the clutch design, material nor function, for example terrorist attack causing gearbox damage, gas turbine and gearbox fires and propeller shaft impact with unexpected subsurface obstructions (Hendry & Zekas (NAVSEA) 2008).

4 Different Hybrid Arrangements

Some established hybrid concepts and others “in build” include:

4.1 Sandown Class Minehunter

The Sandown Class Mine Counter Measures Vessel (MCMV) was conceived around the mid-1980s and entered service in 1989 into the UK Royal Navy and the Royal Saudi Navy. UK assets continue to operate within UK RN and others after transfer. The Spanish Navy continue to operate their equivalent Segura Class design.

The propulsion system layout is identical in all UK, Saudi and Spanish platforms, as illustrated in Figure 6.

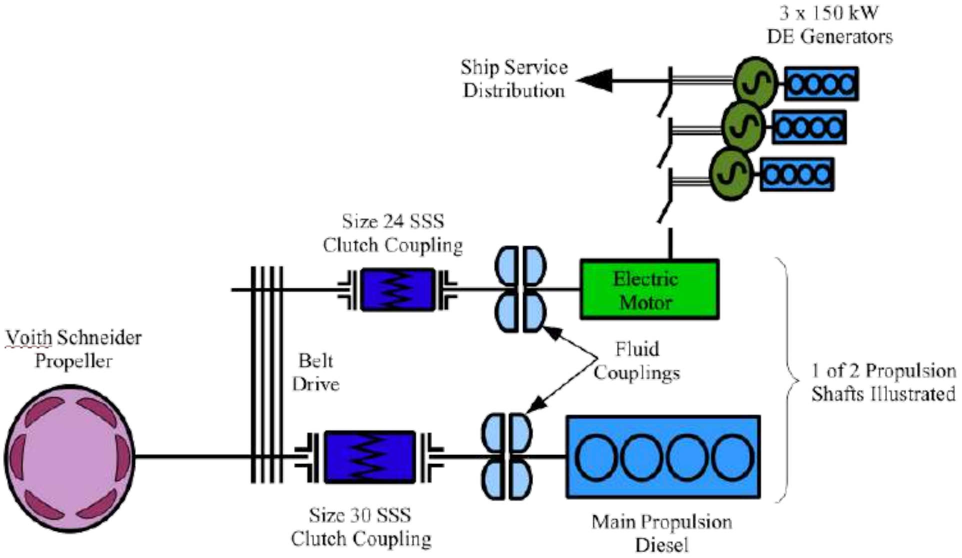


Figure 6: Sandown Class propulsion system layout

The combination of overrunning clutch and fluid coupling simplifies the propulsion controls and reduces the transmission losses normally associated with fluid couplings (cooling, drag etc.) when each prime mover is switched off. The absence of a large MRG and its lube oil system reduces lubrication and cooling losses further, requiring that the gear type overrunning clutch was designed to be self-lubricating and self-cooling. The "SSS Clutch Coupling" design, was further optimised by including the following features illustrated in Figure 7:

- Disc pack flexible couplings taking up adjacent machinery misalignment.
- Internal ball bearings and seals to enable shaft mounting.
- An internal LOCK OUT mechanism to isolate the DE from driving the machinery allowing trip testing, friction plate functional testing, fuel valve balancing and other tests without driving the ship.
- Specially selected materials of construction to reduce the magnetic signature as is necessary for a MCMV.

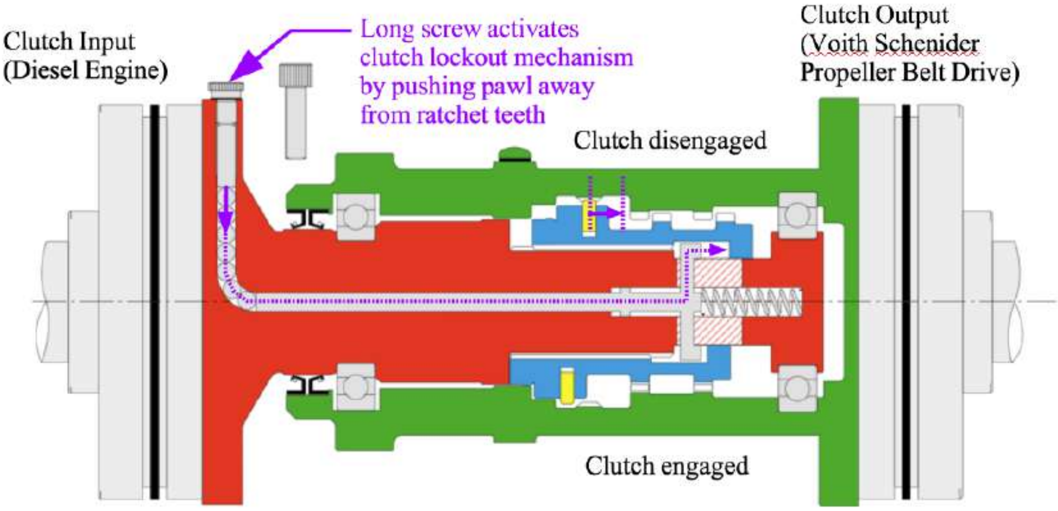


Figure 7: Sandown Class DE propulsion clutch with lockout for diesel engine testing

4.2 FFX-II "Daegu Class" Frigate

The ROKN FFX-II "Daegu Class" propulsion system was developed with similar intent to UK Royal Navy Type 23 "Duke Class", Japanese Navy "Asuka Class" frigates, Spanish Navy F-110 frigates and UK Royal Navy Type 26 frigate. Studies concluded that propulsion system advantages for Anti-Submarine Warfare (ASW) frigates could be achieved by arranging the propulsion machinery to isolate mechanical machinery noise and vibration whilst operating in low speed ASW mode.

Clutch design and placement isolates the mechanical noise transmitted by the gas turbine MRG whilst the platform operates electric motor drive, optimising towed array sonar efficiency in EM / ASW mode.

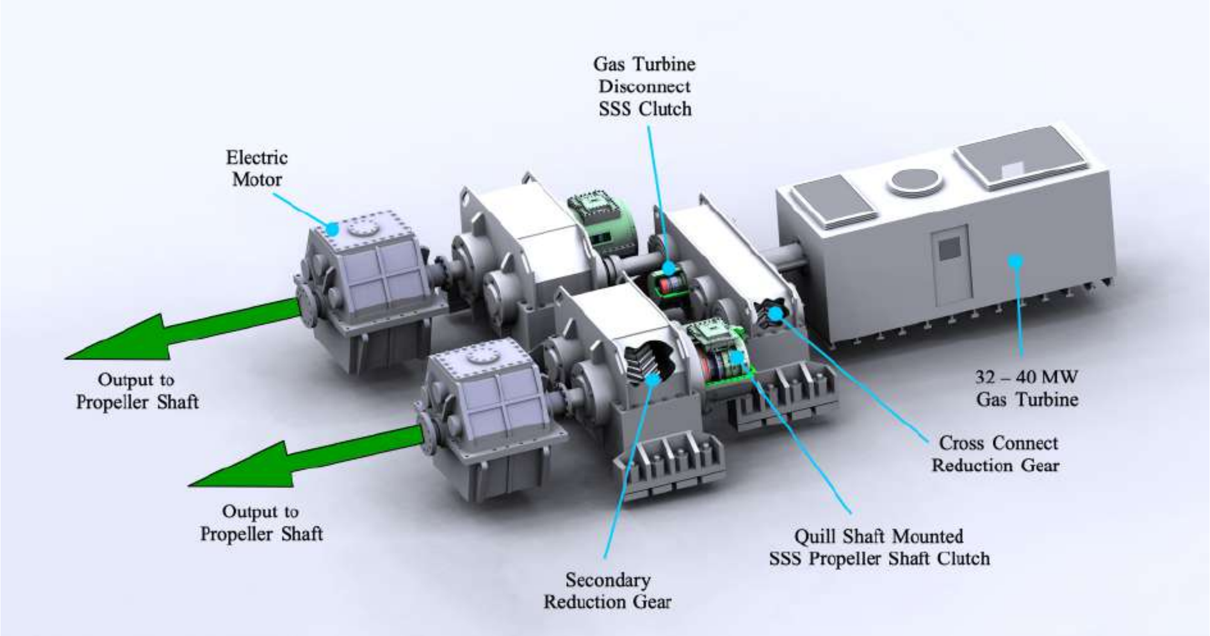


Figure 8: ROKN FFX-II "Daegu Class" Frigate Propulsion System

Of the clutch choices described earlier, cam or sprag type clutches are too small in power / speed capability, leaving two clutch choices, the advantages of each were described in section 3:

- Wet multi-plate friction clutch
- Gear type overrunning clutch.

Only one design, specifically SSS Clutches, have a UK MOD "Fit and Forget" rating and a US Navy rating of >270,000 hours MTBF.

UK RN Type 23, ROKN Daegu Class and Spanish F110 all use quill shaft mounted overrunning gear type clutches, as illustrated in Figures 4b, 8 and 9, offering significant weight and space savings. The lower oil flow required by gear type clutches enables the use of a self-lubricating dip / scraper mechanism, which this paper's author believes is only available to SSS Clutch designs. This further reduces operational risk wherein the clutch continues operating / self-lubricating whilst "locked out" in EM mode, even if the lube oil system has sustained damage.

Only SSS Clutches have plunger / lever operated fully manual override to enable localised operation even after control system "black out" or loss of gearbox oil pressure. Both overrides are regularly rehearsed by extremely capable RN Type 23 engineering crews before ship deployment.

This is not possible with friction plate clutches, which increases risk, because a non-operational auxiliary lubrication system renders only two options:

- EM mode with plates "open" = Risk of plate overheating, creating fire risk.
- Operate in GT mode using emergency gravity fed oil tank = limited range until gravity tank is empty = possible severe damage to gearbox.

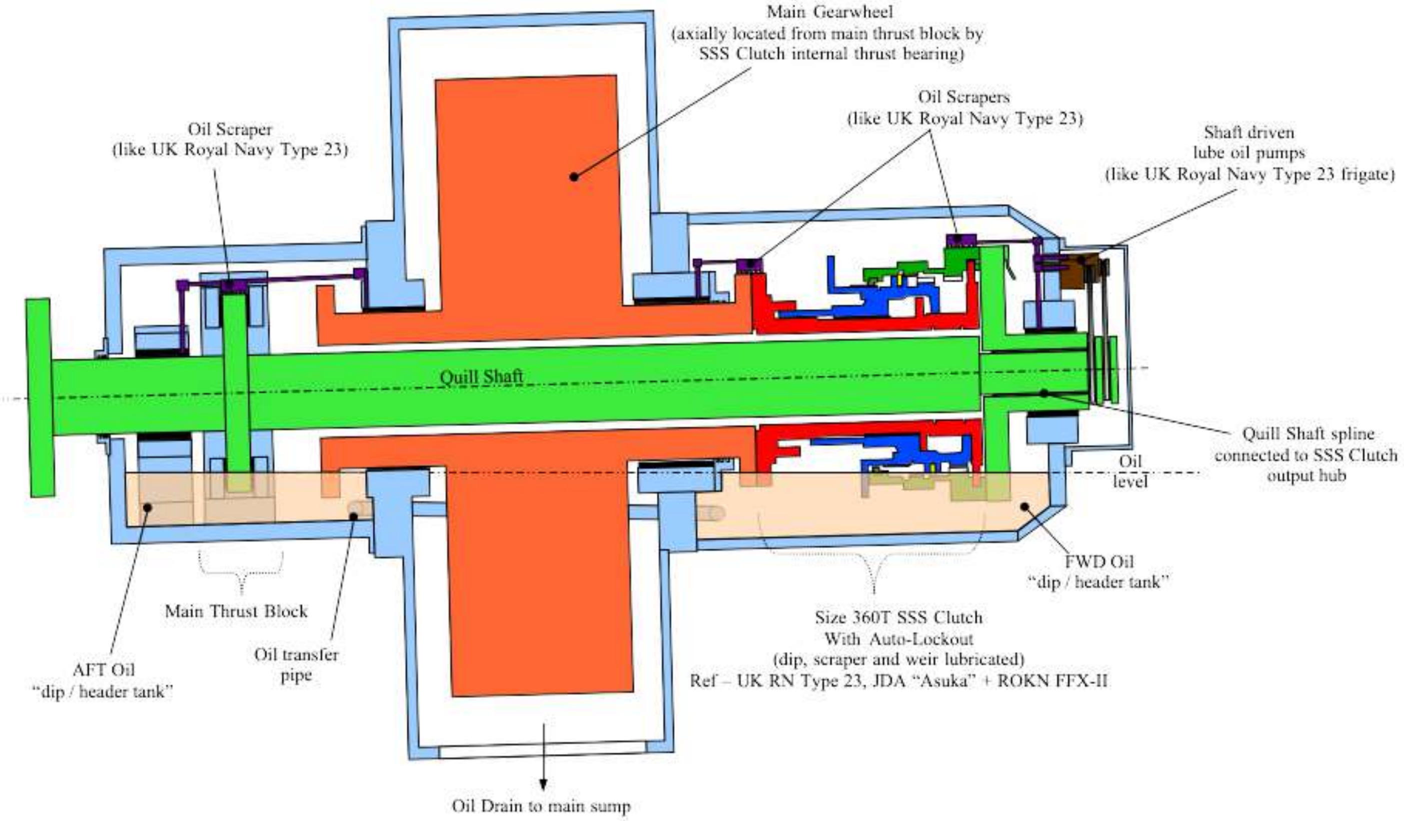


Figure 9: SSS Propeller Shaft Clutch in quill shaft arrangement

4.3 DDG-51 Hybrid Electric Drive Upgrade (>DDG-103)

The US Navy / NAVSEA realised that a significant fuel saving was possible from operating their DDG-51 Arleigh Burke platform at low speed using a hybrid electric drive (HED). Operating gas turbine electrical generators at high load offers increased fuel efficiency compared with operating main propulsion gas turbines at part load.

Electric motor shaft line isolation was specified, reducing single point of failure risk. A hollow "quill shaft" motor and SSS Clutch design was selected to reduce overall axial length associated with "in-line" solutions as illustrated at Figure 10. Each flexible coupling element is located either side of the clutch and the coupling transmission shaft through its centre.

Mechanical lockout and baulked protection (Section 3.3) provides additional safety. Success within the USN DDG-51 HED platform, has been followed by other navies with a similar HED system being added to the ROKN KDX-III destroyer Jeongjo the Great class.

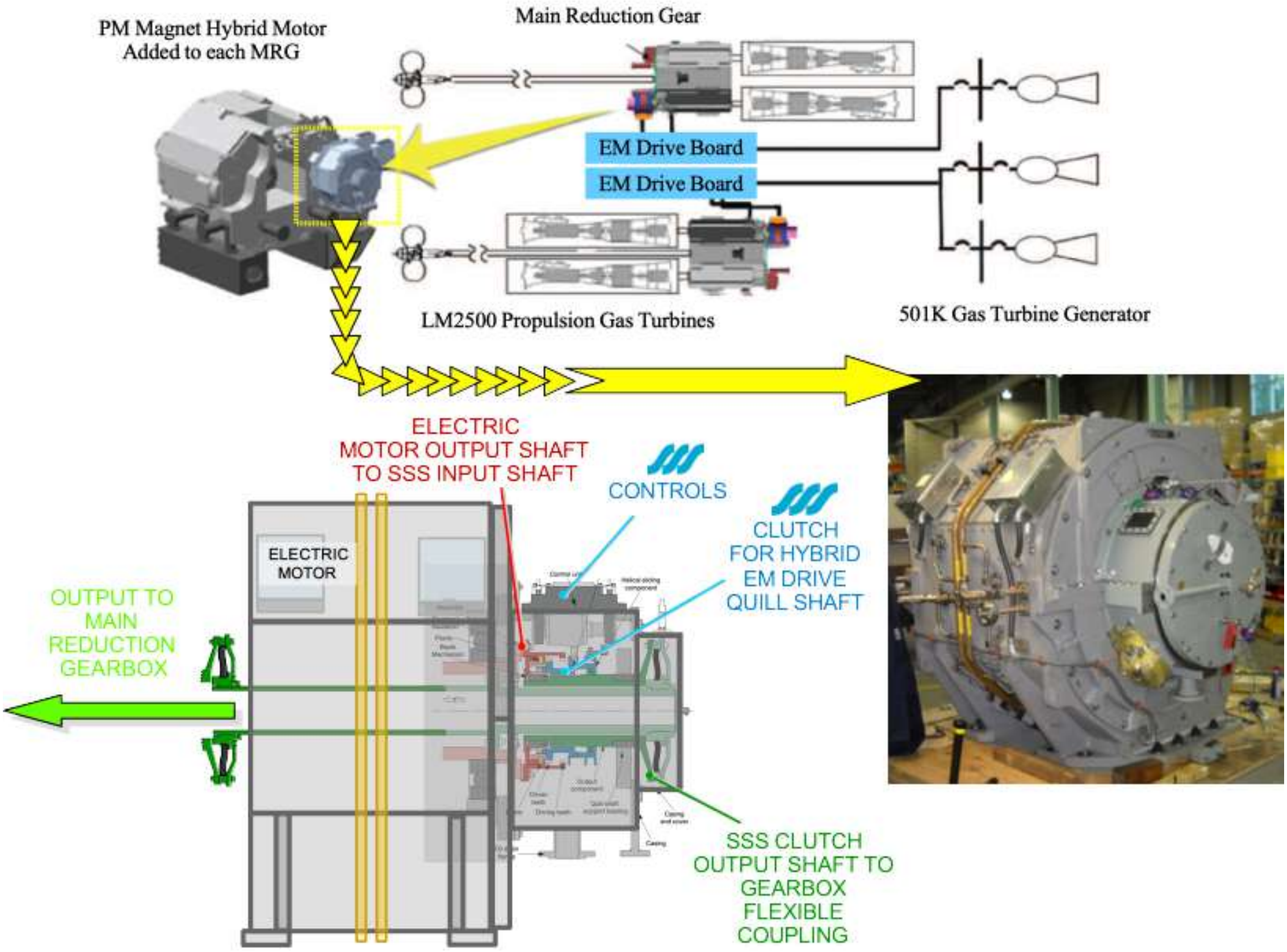


Figure 10: US Navy DDG-51 Hybrid Electric Drive (USS Truxton DDG-103 onwards)

4.4 Future Frigate Propulsion System

Single point of failure incidents caused a rethink amongst some navies, leading to rearrangement of MRG systems with propeller shaft clutches externally mounted, within a separate casing "pod" as illustrated in Figure 11, which includes propeller shaft and gearbox output shaft support bearings.

The same SSS Clutch OEM designed and developed their own self-lubricating and self-cooling oil mechanism, included within the pod. The mechanism, proven by dynamic testing, lubricates clutch and propeller shaft support bearings at all shaft speeds and in both directions of rotation. The platform therefore benefits from no auxiliary lube oil system noise and improved operational efficiency.

Another key advantage enables the clutch pod and MRG to have common oil sumps, because this clutch type uses the same lubricating oil as the MRG, unlike alternative devices (Section 3.1). The oil circulation effect at low-speed pre-heats the clutch / MRG oil, reducing the time required to pre-heat the MRG oil, realising another naval warfare advantage in a clutch design.

This development places the same clutch OEM in the unique future position of becoming a 1st tier propulsion component supplier, as opposed to a sub-tier supplier within the MRG housing.

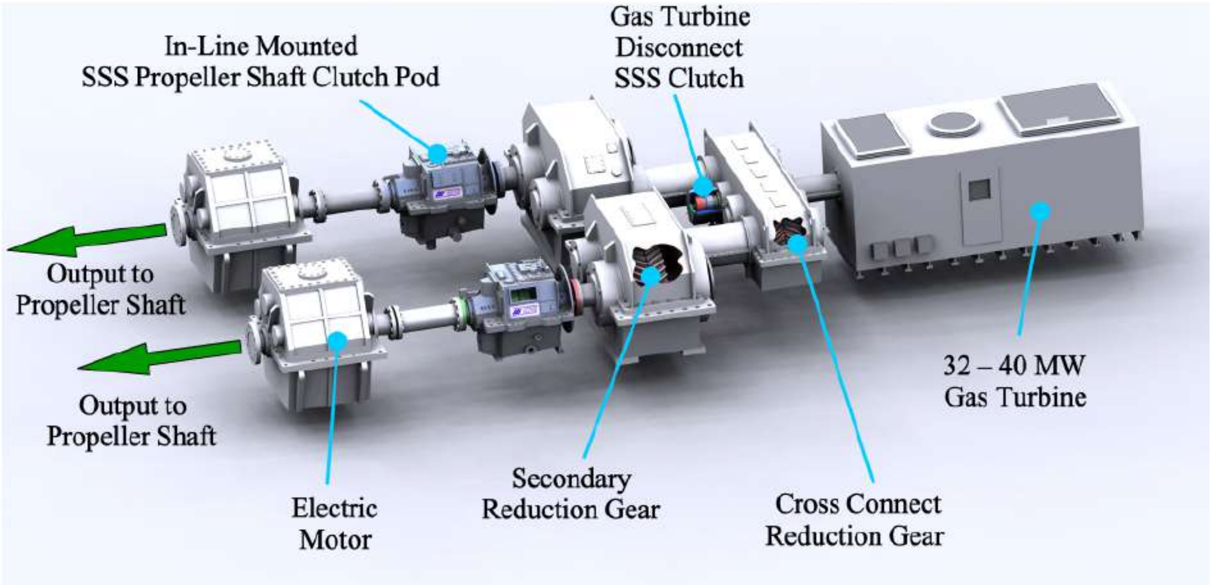


Figure 11: Future Frigate Hybrid Propulsion System with External SSS Encased Clutch

4.5 Hybrid Propulsion Commercial "Fast Ferries"

Gear type overrunning clutches are most common within gas turbine propelled warships, due to their inherent design advantages befitting the high-power density and fast response offered by a sprint mode gas turbine. Friction plates are normally selected for reasons centring around capital cost for lower powered, or slower, propulsion systems. The improved efficiency of gear type clutches have won them recent new contracts for diesel hybrid powered fast ferries in this same power range, whose operators regard reduced emissions and improved fuel efficiency as more important than slightly increased CAPEX.

4.6 "Blackstart" Capability

Gear type clutches have also been retrofitted into gas turbine starting drives for warship turbo-electric generators. Lessons learned from the US Navy concluded that a secondary starting system, driven by an alternative fuel source to the primary starting system as illustrated in Figure 12, was essential to survivability.

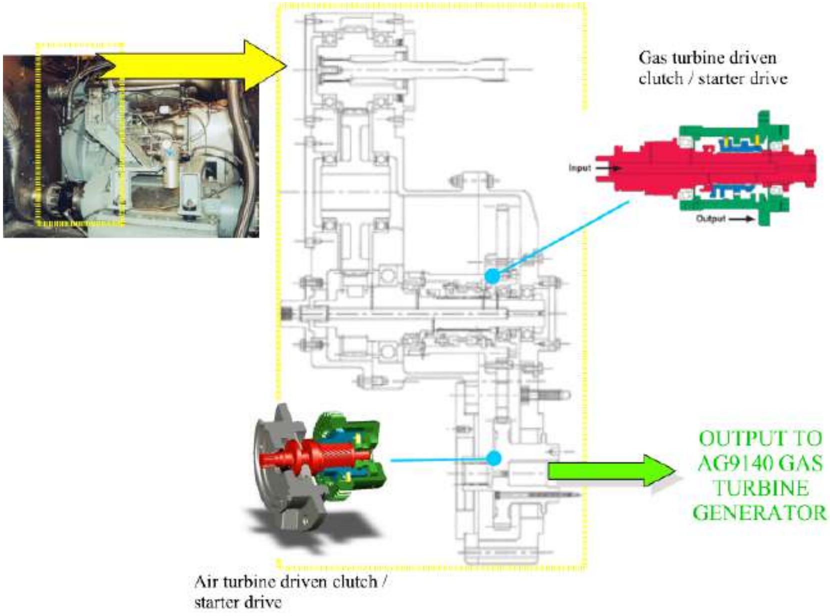


Figure 12: Twin prime mover / twin clutch turbo generator starting drive

The twin drive system now retrofitted into this class of ship, as well as the main propulsion turbines of others, provides the redundancy necessary for other ship systems, including firefighting pumps.

In addition to the redundancy measure mentioned above, the original air starter system included a sprag / roller clutch which suffered repeated failure when moisture within the air supply system caused a torque spike so this was also replaced with a gear type overrunning clutch.

4.7 Future Destroyer Propulsion

Future destroyer programs regularly reference DEWs and large numbers of sea to air vertical launch systems (VLS). Some report the possible use of larger VLS variants (O'Rourke, 2025). Increases in weight and size of VLS, combined with the larger generation requirements of DEWs will of course impact naval architecture, likely increasing hull size and its displacement, thus more propulsive power would be necessary.

Hybrid combination systems, combined with ever more power dense gas turbines and larger electric motors gives the PSI a wide range of options. The requirement to switch from a single gas turbine, connected through a cross connect gear, to two gas turbines with separate MRG systems would naturally relocate the sprint clutch to within the sprint MRGs as illustrated in Figure 13.

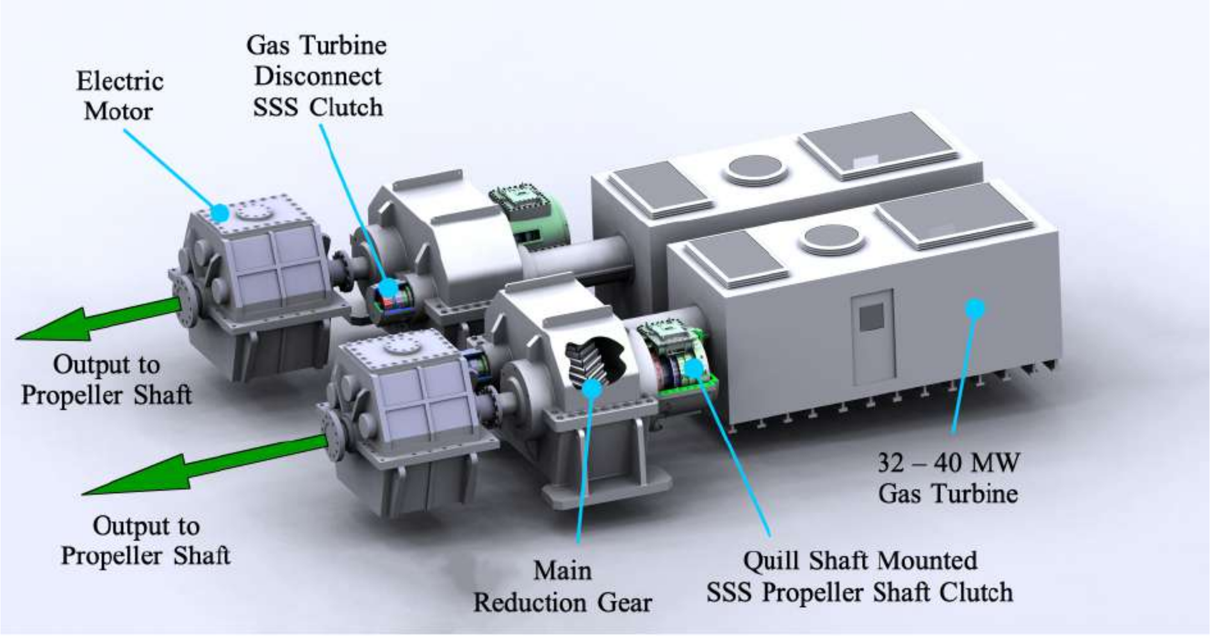


Figure 13: Future Hybrid Propulsion Systems layout for >10,000 TD

5 IFEP Propulsion

5.1 IFEP Propulsion Arrangements

Different motor and drive board options are available to the engineers who are directly coupling those motors to their propulsors. Different propulsor options also exist, which can be generalised into FPP, CRP and pod propulsion systems. Those motors and propulsors all have advantages and disadvantages which are well discussed, which generally fall under subheadings of power, speed, survivability, cost, energy efficiency, noise and basic practicality.

It is reasonable to conclude that one solution does not always perfectly suit all scenarios which the platform might be required. A basic example would be a fixed pitch propeller, driven by a permanent magnet motor, which arguably suits the low speed / low noise requirements.

Once manoeuvrability requirements, particularly AFT propulsion are also considered, the requirement to select a bi-directional motor and drive boards, or change the propeller to a more complicated CRP arrangement, can make the motor type and propeller choice a compromise instead of an optimal solution.

Twin motor arrangements are occasionally selected, wherein each shaft line includes two motors of the same type, which are directly coupled to one another and the propeller. Each motor normally receives its electrical feed from independent electrical drive board to cover redundancy options, whereas optimised survivability is achieved with clutch addition as illustrated in Figure 14.

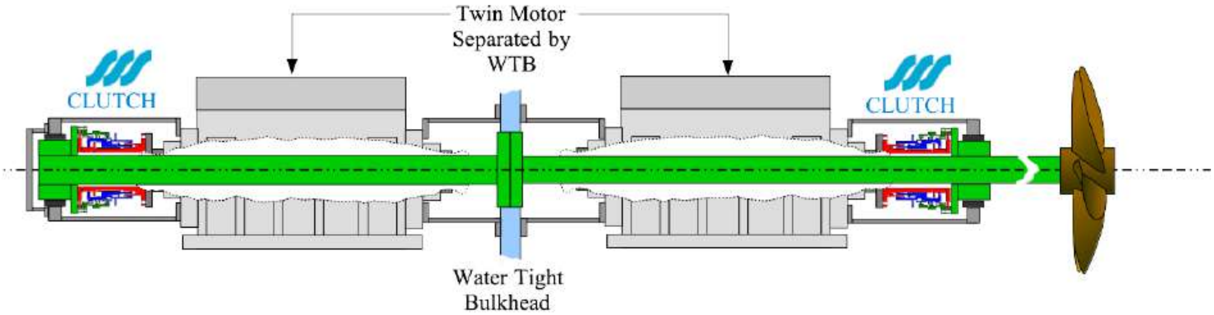


Figure 14: Father / Son Propulsion Motors in AND arrangement for improve redundancy and survivability

With the addition of a clutch, it is also possible to use differing motor sizes and indeed types (PM versus Induction motors) on a common propeller shaft line, without the risk or noise of one type affecting the other's performance as illustrated in Figure 15. Reasoned use of a water tight bulkhead can help counter survivability concerns.

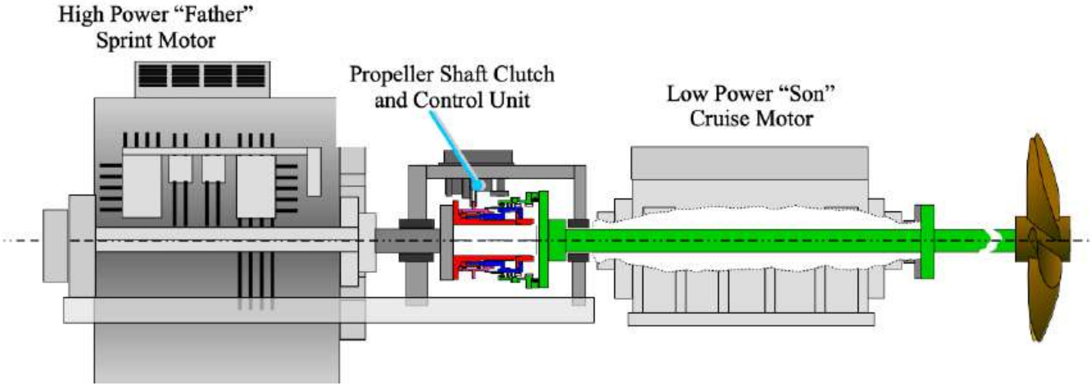


Figure 15: Father / Son Propulsion Motors in AND arrangement for improve redundancy and survivability

As described in section 3, some clutch designs include additional functions which activate or deactivate their automatic engagement and disengagement functions. These were added and proven as long ago as the late 1950's to ensure that platform operational aspects, like manoeuvrability in FWD or AFT modes using various propeller types and optimising noise performance are all covered.

5.2 IFEP Generation Arrangements

The electric motor generation source in IFEP and hybrid propulsion is via prime mechanical movers, most often reciprocating piston diesel engine or gas turbine generators (DG or TG) or a combination of both, and these generators also provide energy for the ship hotel load and naval combat systems. Watertight bulkheads often separate these generators individually or in groups for survivability purposes, as well as their electrical distribution and EM drive systems which distribute their energy.

Devices within combat systems, notably some radar systems and future DEWs are of high-power density (consumption) and their evolutionary development has created a higher demand to the generation systems on which they depend. In addition to the sheer level of power they demand, the frequency at which the power demand can change creates challenges for electrical distribution. Power supply quality problems including electrical harmonic distortion, voltage and frequency modulation caused by pulsed loads creates challenges to all-electric ships (Prousalidis et al 2003 and 2008) so it is reasonable to assume that such challenges will increase as the large pulsed loads associated with DEWs on future naval platforms become more prevalent.

6 Terrestrial Power Generation

Terrestrial power generations systems are often designed to be flexible, allowing a single generator to suit multiple applications and income streams, known as “revenue stacking”.

6.1 Gas Turbine Peak Lopping generators

Gas turbine peak lopping generators, or “peakers” often despatch real power for only a few hours each week, when other generation sources are unavailable. Their prime movers are most often fast stop / start machines, for example gas turbines and reciprocating engines.

The “carbon net zero” goal has caused migration away from turbine driven assets towards renewable technologies like solar PV and wind turbines. Turbine rotors have a large amount of inertia, driving generators at the same grid frequency to which they are connected, referred to as “electrical inertia”.

Solar PV cells have no such inertia. Wind turbines blades rotate at a different frequency to the grid to which they are connected, requiring their electrical connection through inverters, thus their rotating inertia is not connected to the grid.

Electrical inertia slows down grid rate of change of frequency (ROCOF), as adverse grid events occur, for example a power station tripping offline. Additional electrical inertia also increases grid current flow, which in turn helps generate the short circuit current necessary to trip various parts of a grid offline.

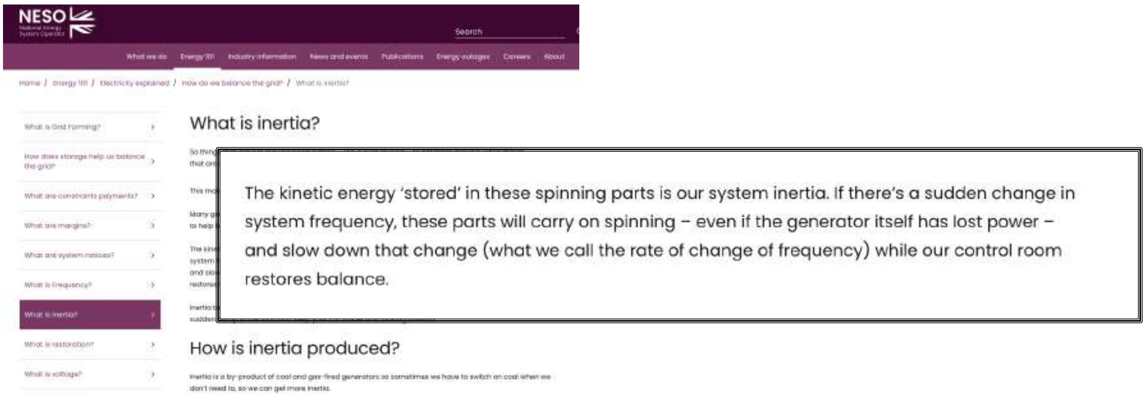
Short circuit current is therefore vital to maintain system voltage (NESO 2020). The UK National Energy System Operator (NESO) has been contracting assets to provide additional inertia since November 2024, traditionally provided by:

- AC synchronous generators, which can operate in generation and motor mode using one set of electrical windings.
- Standalone synchronous condensers - an AC synchronous generator permanently coupled to a pony motor.

In addition to “real power” despatched by a generator to an AC grid, electrical machines also create a movement of background energy called “reactive power”, which can be arranged to benefit voltage levels. Reactive power is formed by electrical machines which produce electric and magnetic fields. The “rush to renewables” has reduced grids abilities to produce reactive power for the same reasons as the decrease in electrical inertia already explained (Robb 2019, Kumar et al 2023). Grids pay assets for providing additional MVARs (NESO Reactive Power Market 2025).

MVAR requirements in electrical grids tend to be geographically dependent, whereas adding inertia is “grid-wide” and therefore, in general, not geographically dependent.

Whilst synthetic inertia can be produced by batteries and power electronics, it is not generated by kinetic energy and therefore described as “grid following”. Inertia and frequency balancing services are instead derived from kinetic energy, or rotating mass, such as a flywheel generator and are therefore instead described as “grid forming”. Terrestrial grids have already identified the benefits which increased spinning inertia bring to battery networks (NESO 2025 – illustrated in Figure 16).



What is inertia?

The kinetic energy ‘stored’ in these spinning parts is our system inertia. If there’s a sudden change in system frequency, these parts will carry on spinning – even if the generator itself has lost power – and slow down that change (what we call the rate of change of frequency) while our control room restores balance.

How is inertia produced?

Inertia is a by-product of coal and gas-fired generators so sometimes we have to switch on coal when we don't need to, so we can get more inertia.

Figure 16: Extract from (UK) National Energy System Operator “NESO” website

A peaking gas turbine generator fitted with a clutch can "revenue stack" by earning payment for two additional forms of grid support when the machine might otherwise be switched off:

- Peak lopping real power (MWe).
- Reactive power (MVARs).
- Inertia (GVAs).

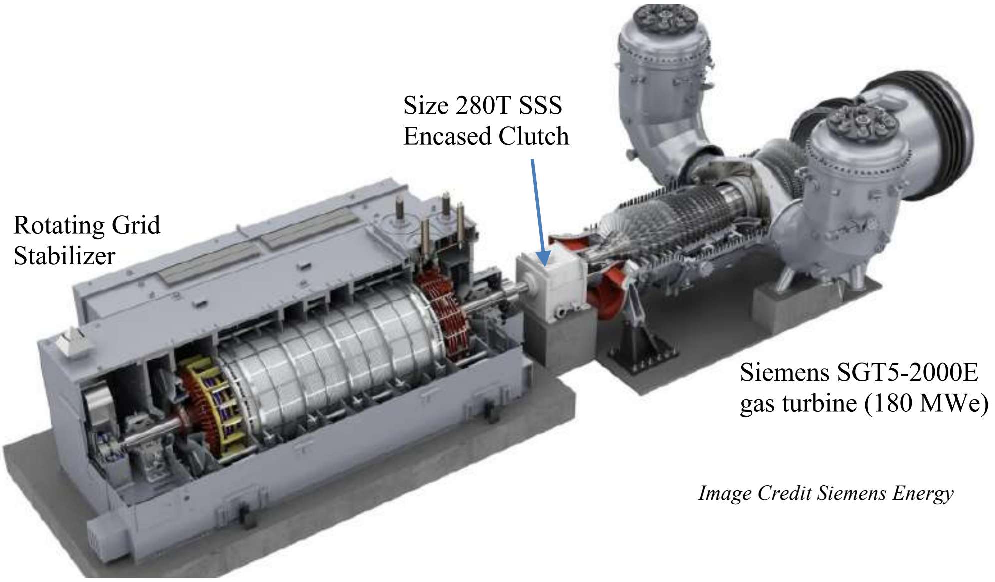


Image Credit Siemens Energy

Figure 17: Siemens Hybrid Rotating Grid Stabilizer conversion for Townsville (RATCH Australia)

Once the generator is synchronised with the grid, the addition of a clutch, as illustrated in Figure 17, allows the asset to correct reactive power and provide additional inertia, whilst the turbine is shut down. Clutch-less machines cannot provide these services whilst the turbine is "switched off". Clutched machines also have improved start-up time, because acceleration / synchronising time is reduced.

Large direct drive industrial and aero-derivative gas turbines can include this benefit, as can geared, lower power / higher speed gas turbines as illustrated in Figure 18.

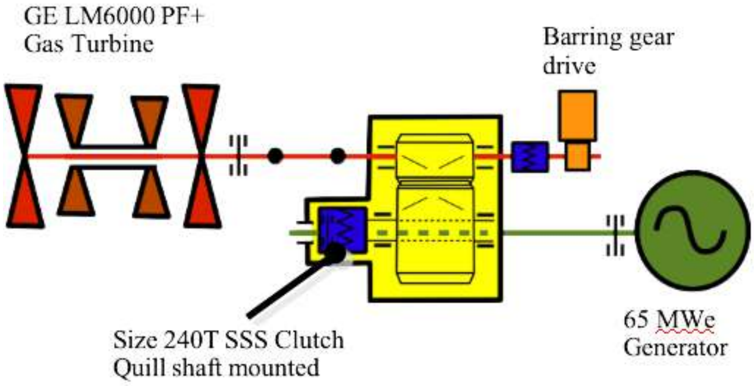


Figure 18: Illustration of machinery layout for GE Vernova LM6000PF+ gas turbine generator / synchronous condenser

First proven at Bristol Siddeley (Rolls Royce) "Patchway" site in 1958, this application now has several thousand global references. Grid privatisations reduced its popularity, but the recent rush for renewables has reversed this as grids create new payment mechanisms to reliably manage voltage control and system frequency response.

SSS Clutch power ratings range from a few hundred kW to >600 MW (2027 scheduled start). Some 1970s references (Malmo, Sweden and Taylor's Lane, UK) still operate as combined synchronous condensers and peak loppers.

6.3 Reciprocating piston engine generators

Clutches have been added to diesel and natural gas engine driven uninterruptible power supplies (UPS) since 1993, to provide ride through power. Increased competition continues between high power density gas turbines and fast response "multi-block" diesel engine arrays which claim more efficient "turn down capacity", thus diesel engine generators also include clutches for revenue stacking. References exist from a few hundred kWe to 13 Mwe, as illustrated in Figure 19.

Self-cooling, self-lubricating, self-supporting SSS Clutch Coupling designs illustrated in Figure 20, are most prevalent in this application, common to all MCMV platforms described in section 4.1.

Clutch Size	**T Nm** lbs.ft	**Max Speed** rpm	**Weight kg** lbs	**Some Engine References**
24	1356 1000	3600	30 65	Refer to SSS
30	3800 2800	3000	60 131	Paxman Valenta 6RP200E Bazan-MTU 6V 396
36	7460 5500	2000	104 230	CAT 3512
42	12610 9300	1800	144 318	INNIO Waukesha 7044 CAT 3516 and 3606
42+	15000 11000	1800	144 318	MTU 16V4000G83
42++	17000 12500	1800	144 318	MTU 20V4000 Cummins QSK78
49	27000 19900	1800	209 462	MTU 20V4000 Cummins QSK78
60	33900 25000	1200	407 897	CAT 3616
98*	160000 118000	750	1042 2297	Refer to SSS

Figure 19: SSS Clutch Coupling sizes and some installed / operating diesel engine references

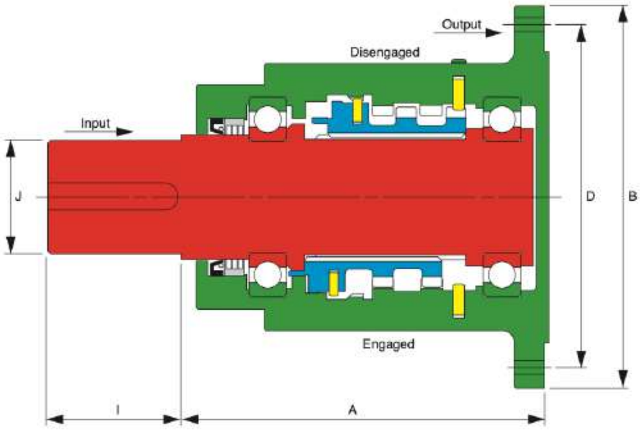


Figure 20: SSS Clutch Coupling design without flexible couplings for generator drives

6.4 Increased Fault Resilience

This new popularity for clutches between diesel engines and generators for revenue stacking has revealed useful additional advantages. If no clutch existed in this application, then a generator overspeed event, or diesel trip event, would result in the entire machine being shut down. With an automatic clutch installed between DE and generator however, its control system can:

- Generator overspeed event –
    - DE set to idle speed, clutch automatically disengages and generator remains spinning.
    - Clutch automatically re-engages once generator speed reduces to DE idle speed.
    - DE accelerates back to synchronous speed and re-closes breaker.

- DE misfire –
    - DE set to idle speed, clutch automatically disengages but generator remains spinning / synchronised with grid.
    - DE misfire fault cleared.
    - DE accelerates to synchronous speed, clutch automatically engages and generator provides MWe.

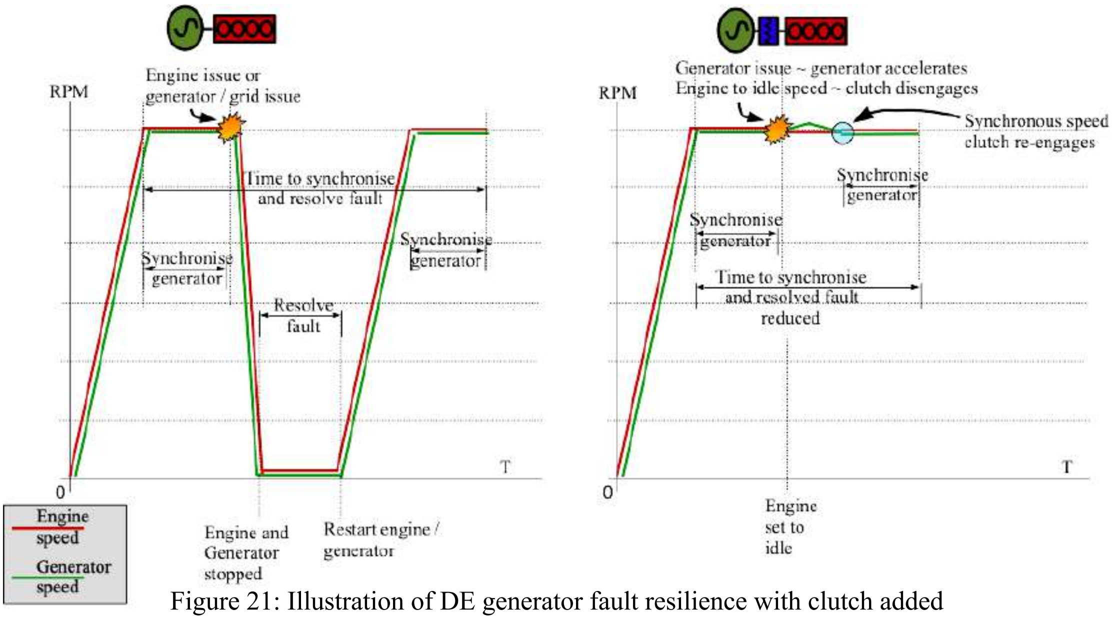


Figure 21: Illustration of DE generator fault resilience with clutch added

This sequence of events illustrated in Figure 21 reduces the downtime for machinery fitted with automatic clutches providing a strategic naval warfare advantage.

7 DEWs and EMALS

Most Direct Energy Weapons (DEWs) advantages stem from replacing their disposable propelling action with electrical energy. The removal of propellants like steam (aircraft catapult) and nitrocellulose / nitro-glycerine, as well as the equipment necessary for its generation, safe storage and handling all lead to these advantages.

As is the case with all advantages, it is essential to ensure that the technical challenges created by the alternative technology does not create an overall disadvantage. In the case of DEWs which are designed with sufficient propulsive force to match the accuracy, range and firing frequency of traditional catapults and munitions, those challenges include not only generating vast amounts of electrical energy, but also ensuring that its recharge rate and efficient distribution is adequately managed.

Various methods of generating, storing and distributing this energy have already been discussed and battery energy storage systems (BESS) within warships are well documented (Belvisi et al 2024, Karlsson et al 2024).

Flywheel energy storage systems are already adopted into future DEWs, notably laser development for the UK MOD (IMechE 2019, Allison 2019, RINA 2020).

Experimental generation machines called compensated pulsed alternators or “compulsators”, which combine a specially wound alternator and kinetic energy flywheel have also been developed using US Military funding by the University of Texas Centre of Electromechanics, for use with experimental railguns. The windings of this machine were specifically designed to minimise inductance, making the machine better suited to the delivery of pulsed energy for high powered DEWs (Kitzmiller et al 2003, Walls 2002).

Compulsators were designed to be spun up to operating speed by an additional pony motor. A gear type overrunning clutch was supplied by SSS Gears in the mid-1980’s to enable separation of the pony motor and compulsator, just as the same clutch types are now used within electrical grids to separate the generator flywheel from their prime movers.

The type of electrical generator best suited to operate as a combined flywheel will of course require further research and several known options already exist providing ride through power and it may well be the case that a combination of batteries and flywheel provide the optimum choice.

8 Conclusions

Replacing chemicals and high-pressure steam with electrically powered DEWs poses challenges beyond the level of required power, including rapid recharge and efficient distribution. Distribution must also consider that:

- ROCOF (section 6.1) must not cause “trip events” whereby critical propulsion machinery, combat or safety systems like firefighting pumps are disabled.
- Sufficient fault current exists to trip uncritical systems, ensuring critical system continuance.
- Electrical harmonic noise does not compromise stealth.

As already described within Section 6, global terrestrial generation power generation grids have solved similar distribution and ride through power challenges by retaining rotating or kinetic energy on the grid, simply by adding robust and reliable clutches between their existing prime movers and electrical generators.

Some clutches are dual proven through 60+ years of experience within power grids and warships of the world’s largest combined group of NATO aligned navies. These clutch designs have survived physical and software shock testing to MIL standards. They have also survived naval collisions, equipment explosions and terrorist attacks (Hendry & Zekas 2008).

Many different electrical generator designs are available to power system integrators, already designed and proven to make use of their kinetic energy, in addition to their core generation function.

It therefore makes sense to consider modifying existing traditional rotating generations systems on warships by adding clutches, as illustrated in Figures 22 and 23. Machinery which might otherwise be switched off may then help energy distribution and storage systems like BESS to improve DEW integration. Again, this harmony of two existing technologies enables a “grid forming” solution is realised as opposed to reliance on “grid following” technology.

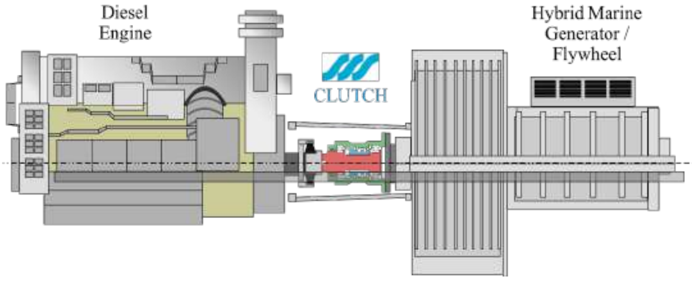


Figure 22: DE Driven Hybrid Marine Flywheel / Generator

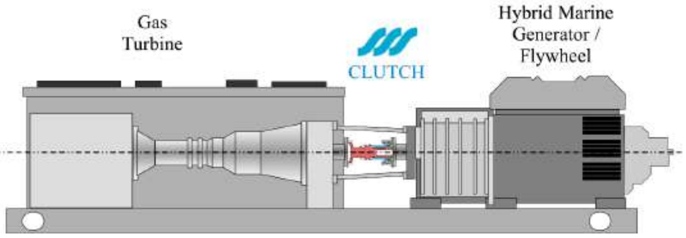


Figure 23: Gas Turbine Driven Hybrid Marine Flywheel / Generator

Combining battery technology and motor flywheel / generators, for “ride through power” in a naval system can be described as “operational stacking”, as terrestrial grids refer to similar processes as “revenue stacking”.

The 2025 UK Government Strategic Defence review describes a Systems of Systems Approach, or “SOSA” as being key to the future UK Royal Navy realising its best potential in optimising Future Air Dominance Systems or “FADS” (Navy Lookout 2025).

The proposals outlined in this paper embrace the SOSA concept within the power generation machinery, DEW combat and other ship’s electrical distribution systems, whereby a combination of system functions help support one another to resolve well-known challenges, as opposed to remaining idle at times and considered as separate systems; QED “Engine ***is*** a Weapon”.

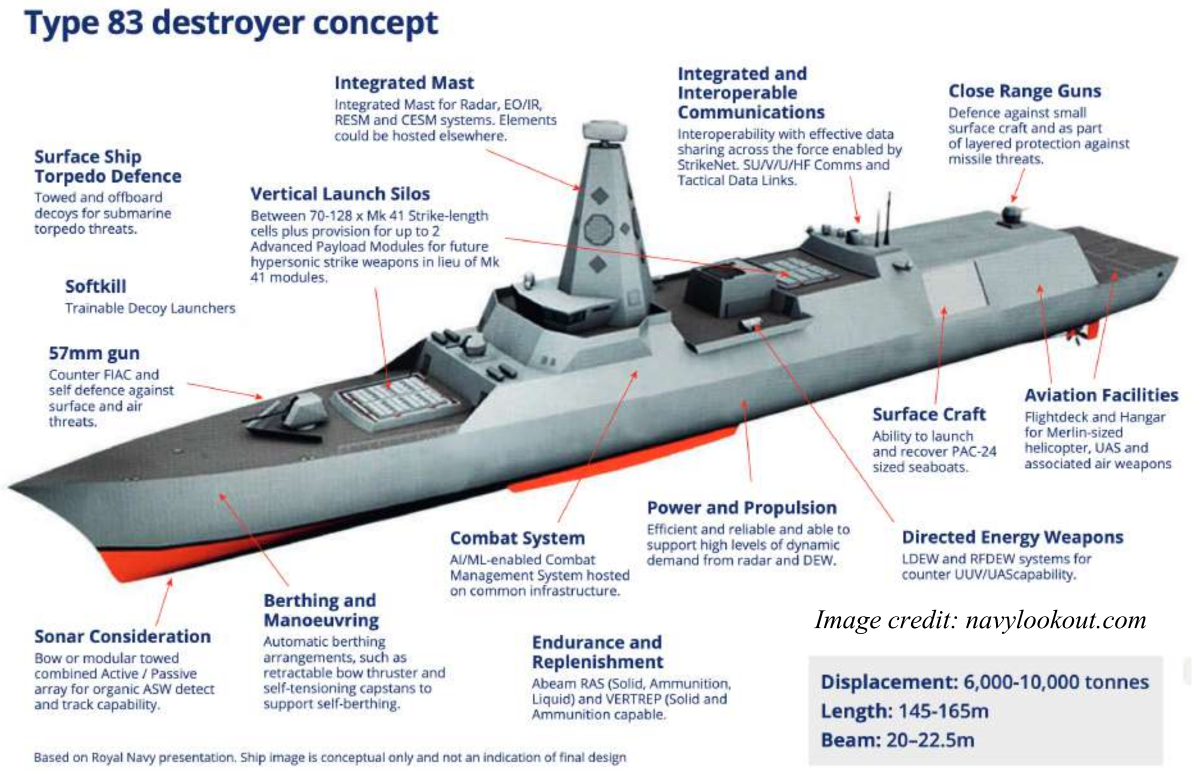


Figure 24: Type 83 destroyer concept

Alphabetical Glossary of terms

AC – alternating current.

AFT (drive) – Propulsive effort to drive ship aftwards, or in reverse.

ASW – Anti-Submarine Warfare.

CAPEX – Capital Expenditure

CCG – Cross Connect Gear

CODELAG – Combined Diesel Electric And Gas

CODELOG – Combined Diesel Electric Or Gas

CODELOD – Combined Diesel Electric Or Diesel

CPP – Controllable Pitch Propellor, normally capable of both AFT and FWD propulsive effort.

DC – Direct Current.

DE – Diesel Engine

DEW – Direct Energy Weapon, for example laser, railgun.

DG – Diesel Generator

EM – Electric Motor

EMALS – Electro Magnetic Launch System, for example an aircraft carrier catapult.

FADS – Future Air Dominance System.

FWD (drive) – Propulsive effort to drive ship forwards.

FPP – Fixed Pitch Propeller

GT – Gas Turbine

GVAs – Gigavolt Ampere seconds (equivalent to Gigajoules, "GJ")

GJ – Gigajoules

HYBRID – Combination of electrical and mechanical prime movers to achieve propulsive force.

HED – Hybrid Electric Drive.

IFEP – Integrated Full Electric Propulsion

MCMV – Mine Counter Measures Vessel

MRG – Main Reduction Gear.

NESO – (UK) National Energy System Operator.

PV – (as in solar) photovoltaic

ROCOF – Rate of Change of Frequency

SSS – Synchro Self-Shifting

ST – Steam Turbine

SOSA – System of Systems Approach

TG – Turbo Generator, wherein turbine can be **GT** or **ST**.

UPS – Uninterruptible Power Supply.

WTB – Watertight bulkhead.

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