Mission-centric Design Of Hybrid Propulsion Systems For Multi-purpose Naval Vessels

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ABSTRACT

In the last few decades the design of naval vessels has gone through substantial changes, moving from a rigid hierarchy of highly specialized vessel archetypes, to considerable more flexible platforms designed to cope with a much wider spectrum of tasks, from disaster relief to constabulary and environmental protection operations, from low intensity conflicts up to full-scale maritime interdiction.

These new requirements exposed the clear limits of traditional naval propulsion plants and, driven by the rapid breakthrough in the field of power electronics and automation systems, opened the way to the development and implementation of innovative solutions, which not only fulfil the required flexibility but provide unprecedented levels of efficiency, redundancy and environmental compliance.

This paper presents:

- a brief overview of the most notable hybrid propulsion plants for naval applications;
- an analysis of the typical operational requirement of a modern multi-purpose naval vessel;
- a practical approach to the design of a battery-hybrid propulsion plant optimized on the above mentioned operational requirements and based on the combination of recent and established technologies, including: high-speed diesel engines, variable frequency drives, electric propulsion motors, batteries, exhaust after-treatment systems, and controllable pitch propellers;

- an assessment of the intrinsic advantages of such a design compared to mechanical, diesel-electric or alternative hybrid solutions;
- a concise outlook on future developments.

INTRODUCTION: THE QUEST FOR FLEXIBILITY

Having the right tool for the job is a lesson early learnt by any seafarer. Naval operations are no exception in this regards: being fit for the task, or actually fitter than your opponent, is critical for success.

Over centuries the increasing extent of naval tasks shaped fleets into rigid hierarchies of highly specialized vessels, a pattern so ubiquitous and well-recognized to be reflected still today in the officer ranks. While the technological advancements in marine propulsion introduced since the beginning of the last century, paved the way to new solutions for efficient operation across a broad speed range, such as combined mechanical/electrical plants (CODAD, CODOG, CODELAG, etc.) and integrated electric propulsion (IEP), it was the 21st century, with its well-known changes in geopolitics, to quickly escalate the urge for operational flexibility.

Modern navies are asked to cover the full intensity spectrum in both green and blue waters with fewer vessels, contracted financial resources and reduced crews, thus requiring multi-purpose and dual use platforms.

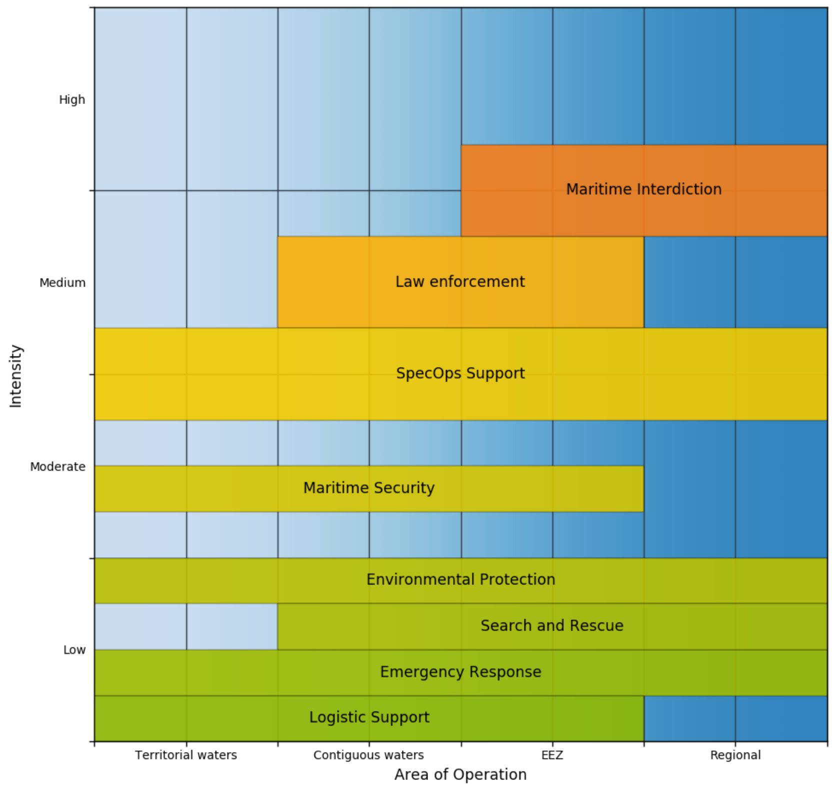
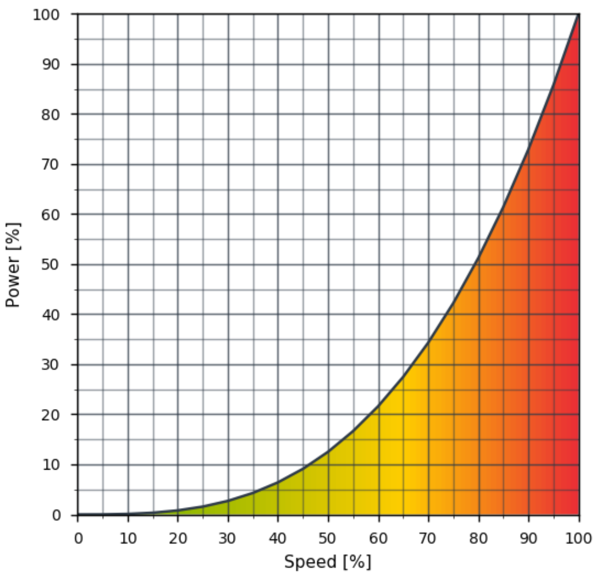


Figure 1 – Operational spectrum of a multi-purpose second line naval vessel

A review of all recent naval designs clearly shows a converging trend toward flexible platforms capable of performing the whole spectrum of tasks traditionally assigned to a variety of second line vessels, such as:

- Maritime Interdiction (deterrence and denial)
- Law enforcement (border protection, fishery surveillance, illegal traffic prevention)
- Maritime Security (intelligence collection, surveillance and protection of assets)
- Marine Environmental protection (prevention, containment, decontamination)
- Special Operations Support (mine countermeasures, diving, hydrography, medical assistance, maritime signaling, etc.)
- Search and Rescue
- Emergency Response (disaster relief, personnel evacuation, salvage)
- Logistic Support

From a propulsion perspective, the immediate issue in dealing with such a broad range of missions is the disproportion of power necessary to achieve the required speed. Even with the latest fuel injection and turbocharging technology a diesel engine (or any other internal combustion prime mover) cannot efficiently operate across such a broad range.



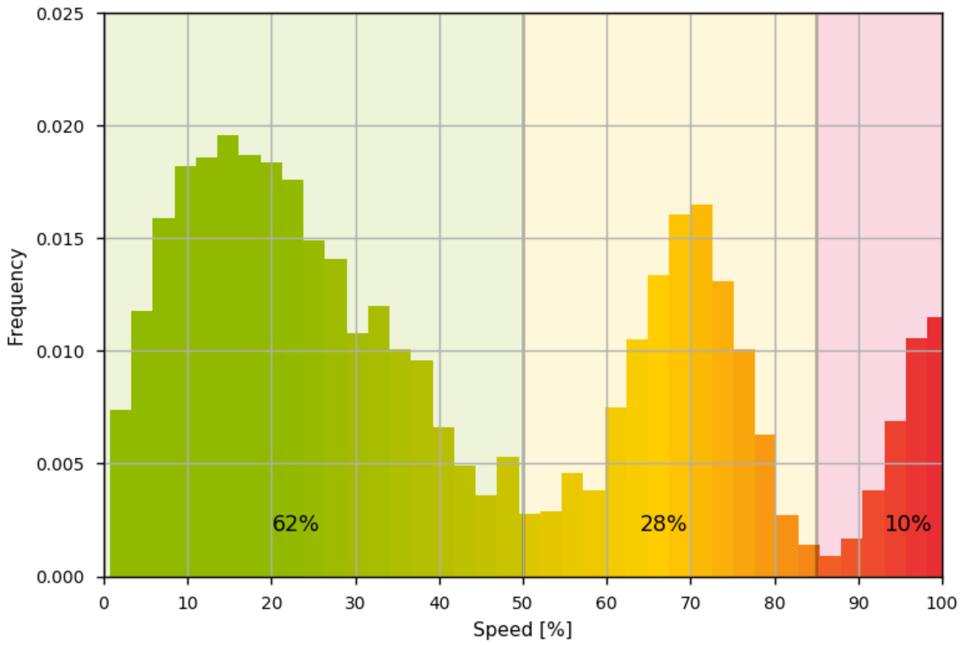


Figure 2 – Exemplary power curve and speed spectrum of a multipurpose vessel

The use of combined mechanical propulsion plants is a classic solution to partially overcome this problem and allow cruise speeds significantly lower than the required maximum speeds (i.e. traditional frigate/destroyer design), but it is still not helpful when an extended loitering mode is required. Electric motors, on the other hand, being able to efficiently operate across an entire power range, represent an optimal solution for such tasks. However, they require significant space as they rely on generating sets and their volume, including drives, is not linear with installed power, making the integrated electric propulsion (IEP) a viable solution only for large vessels.

Since the early 2000s, driven by the considerable advancements in electric equipment, power electronics and automation, hybrid propulsion plants have collected growing interest in both naval and commercial applications[1]. Beside the immediate advantage of combining the operational flexibility of the electric motor with the power density of a conventional prime mover, they offer increased redundancy, higher overall efficiency, faster response and a reduction of the maintenance costs connected to off-design operating points. In addition, due to the rapid development in battery technology the possibilities to include energy storage systems for applications on ships have nowadays occurred. This additional source of energy can be easily integrated in hybrid systems increasing their flexibility. Stored energy might be used to operate the engines and the gensets as close to their design points as possible, to immediately feed the

[1] Even if the first modern Combined Diesel Electric And Gas (CODELAG) plant was commissioned in 1990 on the *HMS Norfolk*, it took almost 20 years for this design to be widely adopted: *USS Makin Island* (CODELOG) was commissioned in 2009, *FS Aquitaine* (CODELOG) and *HNLMS Holland* (CODELOD) in 2012, *ITS Bergamini* (CODELAG) in 2013, *FGS Baden-Württemberg* (CODELAG) in 2016. For a comparison: *Carolyn Dorothy* (tugboat) was commissioned in 2009, *MV Hallaig* (double-ended RoRo ferry) in 2013 and *Prinsesse Benedikte* (RoRo ferry) was retrofitted with a hybrid plant in 2015.

electrical motors for boosting the vessel speed or to be an alternative energy for a certain time reducing noise and exhaust gas emissions.

The potential of battery-hybrid systems is, thus, to provide energy and to control the power delivered by, or to, the shaft machine, in the most efficient way as possible taking all advantages of the electrical and mechanical components. To exploit the potentials of battery-hybrid systems, MAN Diesel & Turbo has developed the advanced and flexible HyProp ECO propulsion system, successfully installed in several types of different marine applications with remarkable benefits in terms of operational flexibilities and operational expenses (OPEX).

In the wake of the trend taking hold of the automotive industry, batteries are getting more and more affordable with reduced overall footprints, weights and costs. However, since the real potential lies in overall optimization, a proper system design requires a detailed knowledge of vessel operating modes and a thorough understanding of each component. Several optimization techniques have been extensively investigated in the technical literature but they all assume a reliable modelling of vessel usage and equipment performance. While the first topic usually resides in a single source (either shipyard or operator), the second one is potentially spread across several solution providers, making a seamless integration of expertise in different fields a key factor for a successful battery-hybrid design.

OVERVIEW OF SELECTED TECHNOLOGIES

High speed diesel engines

Traditionally confined to special marine applications (restricted service, sport and leisure crafts, and fast small naval vessels), high speed engines are now largely selected as prime movers for both commercial and governmental applications.

The advancements in fuel injection technology and engine automation, together with the general trend for lower emissions and cleaner marine fuels, have boosted efficiency, flexibility and reliability. Combined with traditional advantages, such as higher power density and reduced footprint, these features tipped the scales making high speed engines a typical choice for a variety of vessels, from harbor tugboats to superyachts, from offshore supply vessels to frigates.

In order to fit such a wide range of applications high speed engines are typically available in several ratings. The same engine architecture can therefore be tuned to light, medium or heavy duty load profiles, with different rated powers, optimized operating ranges and service intervals, providing designers an additional degree of freedom to tailor the propulsion system to specific requirements.

Exhaust after-treatment systems

In the last two decades, following a well established trend in onshore applications, ship emission limits have been significantly reduced. The latest IMO regulation, already enforced in US and Caribbean waters and soon entering into force in the North and Baltic Seas, set a limit which simply exceeds the capability of engine internal measures without compromising efficiency, reliability and service costs.

On the other hand both automotive and stationary applications have already extensively adopted the Selected Catalytic Reduction technology, proving its technical and commercial effectiveness.

Solutions based on this solid experience are currently the best pick for marine plants, providing several advantages:

- usage of a non-hazardous, safe-to-handle, largely commercially available diesel exhaust fluid (DEF) such the automotive AdBlue;
- no interference with engine operation, cancelling any risk of reliability reduction;
- flexibility of operation, making it possible to activate it only in relevant Emission Control Areas (ECAs);
- lower operational expenses, achieved by optimization of fuel and DEF usage.

Controllable pitch propellers

With over a century of history[2], controllable pitch (CP) propellers are among the most mature and reliable products in the marine industry. Latest developments in computational hydrodynamics and continuous refinement in actuator designs allowed a significant reduction of both the efficiency and maintenance cost gap with fixed pitch propellers, making CP propellers an excellent tradeoff among capital expenses (CAPEX), propulsion efficiency, operational flexibility and operating expenses (OPEX). These benefits can even be increased by using appropriate Efficiency Improving Devices (EID) such as Kappel propeller blades and rudder bulbs. Additionally, CP propellers can be "feathered" when not in operation, significantly reducing the drag and the related negative effects on ship motion of locked/windmilling fixed pitch propeller, therefore providing great operational flexibility.

Electric motors, variable frequency drives and energy storage systems

The concept of electric propulsion is not new, however, with the possibility to control electrical motors by means of frequency converters in a large power and speed range with compact, reliable and cost-competitive electronic solutions, the use of variable speed drives has emerged in electric propulsion since the 1990’s.

The following characteristics summarize the main advantages of electric propulsion:

- improved life cycle cost by reduced fuel consumption and maintenance, especially where there is a large variation in load demand;
- reduced vulnerability to single failure and high availability of power in the system;
- possibility to optimize the loading of the prime movers;
- less space consuming and more flexible utilization of onboard space increases the payload of the vessel;
- less propulsion noise and vibrations since rotating shaft lines are shorter, prime movers are running on fixed speed, and using pulling type propellers gives less cavitation due to more uniform water flow.

[2] The first Alpha CPP design was produced in 1902 and patented in 1903.

When integrating an energy storage system (batteries) to an electric propulsion plant a further degree of freedom can be utilized and can be used to optimize the complete system:

- charging and discharging the batteries in such a way that it optimizes the operating point of the running Diesel engines (“Strategic Loading”);
- fewer Diesel engines needed online as batteries are the backup for running gensets (“Electrical Spinning Reserve”);
- leveling the power seen by the Diesel engines and taking away transient loads (“Peak Shaving”);
- instant power in support of running Diesels (“Dynamic Support”);
- reduced engine running hours;
- zero Emission operation possible (i.e. in harbor).

CASE STUDY: SECOND-LINE NAVAL VESSEL BASED ON NORCAN 222 ERRSV DESIGN

Due to their inherent flexibility, ship designs developed for Offshore Supply Vessels (OSV) have been commonly used as blueprints for second-line Naval vessels. OSVs have excellent seakeeping capabilities combined with high speed and superior maneuverability, they offer a large deck to accommodate containerized equipment for a wide range of special operations and can efficiently transfer solid and liquid cargo.

Initially used mainly for Coast Guard offshore cutters and governmental auxiliary and research vessels, the designs have recently been selected also for multi-purpose naval vessels. Most notable recent examples are the Bâtiment multi-mission (B2M), selected by the French Navy to perform a wide range of tasks in the overseas territories (world's largest EEZ) and the Italian Navy Multi-purpose Submarine Rescue Ship (USSP), capable of a large spectrum of operations, including hydro-oceanographic research at high-latitudes and diving support.

Following these recent examples, we selected the NorCan 222 Emergency Response Rescue and Support Vessel (ERRSV), a modern and innovative OSV design, as a reference platform for a Flag Ship case study.

The NorCan 222 ERRSV is a multi-purpose vessel designed to transcend the traditional ocean-going service vessel capabilities. By combining high-speed capabilities, state-of-the-art hybrid propulsion and latest emission control technology, the NorCan 222 ERRSV is able to perform both emergency response/rescue operations and transport of personnel/cargo more effectively and efficiently than traditional OSVs. The high emergency response speed (up to 34 knots), enhanced seakeeping performance, high maneuverability (DP2 certified), capability of operating at extreme latitudes, availability of specialized equipment (e.g. towage, oil spill response, fire fighting, fast rescue crafts) and spacious load deck (360 m2) are all key features for a second-line multipurpose naval vessels, making the NorCan 222 ERRSV a perfect match for the job.

Figure 3 – NorCan 222 Emergency Response Rescue and Support Vessel.
Courtesy of NorCan Marine Inc.

Length overall	67.7 m (222')
Beam	12 m (40')
Draught	1.76 m (5.8')
Maximum speed	34 knots
Economic speed	27 knots
Bollard pull	80 tons
Fuel capacity	400 m^3
Fresh water capacity	200 m^3
Classification	LR ✠A1 or equivalent

Table 1 – NorCan 222 ERRSV characteristics

The propulsion concept is based on four controllable pitch (CP) propellers turning in a specially designed matched propeller tunnel. The combination of the propeller design and shape of the tunnel, specially designed and optimized for each application results in an unmatched propulsive efficiency.

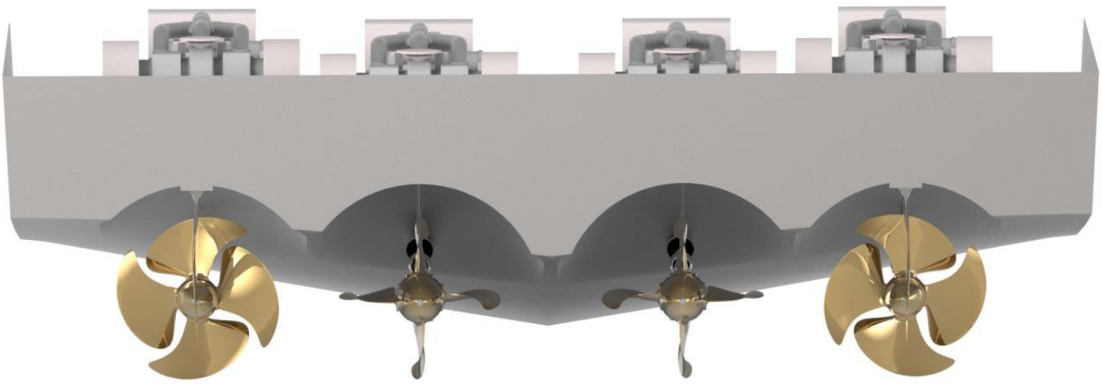


Figure 4 - Transom view, showing inner propeller feathered for minimum resistance.
Courtesy of NorCan Marine Inc. & Servogear AS

The outer shafts, or wing units, deputed to low and cruise speeds are powered by an AKA XeroPoint® Hybrid Propulsion in combination with a CP propeller.

The inner shafts, reserved to high transfer speeds, are powered by a conventional diesel mechanical system with a featherable CP propeller.

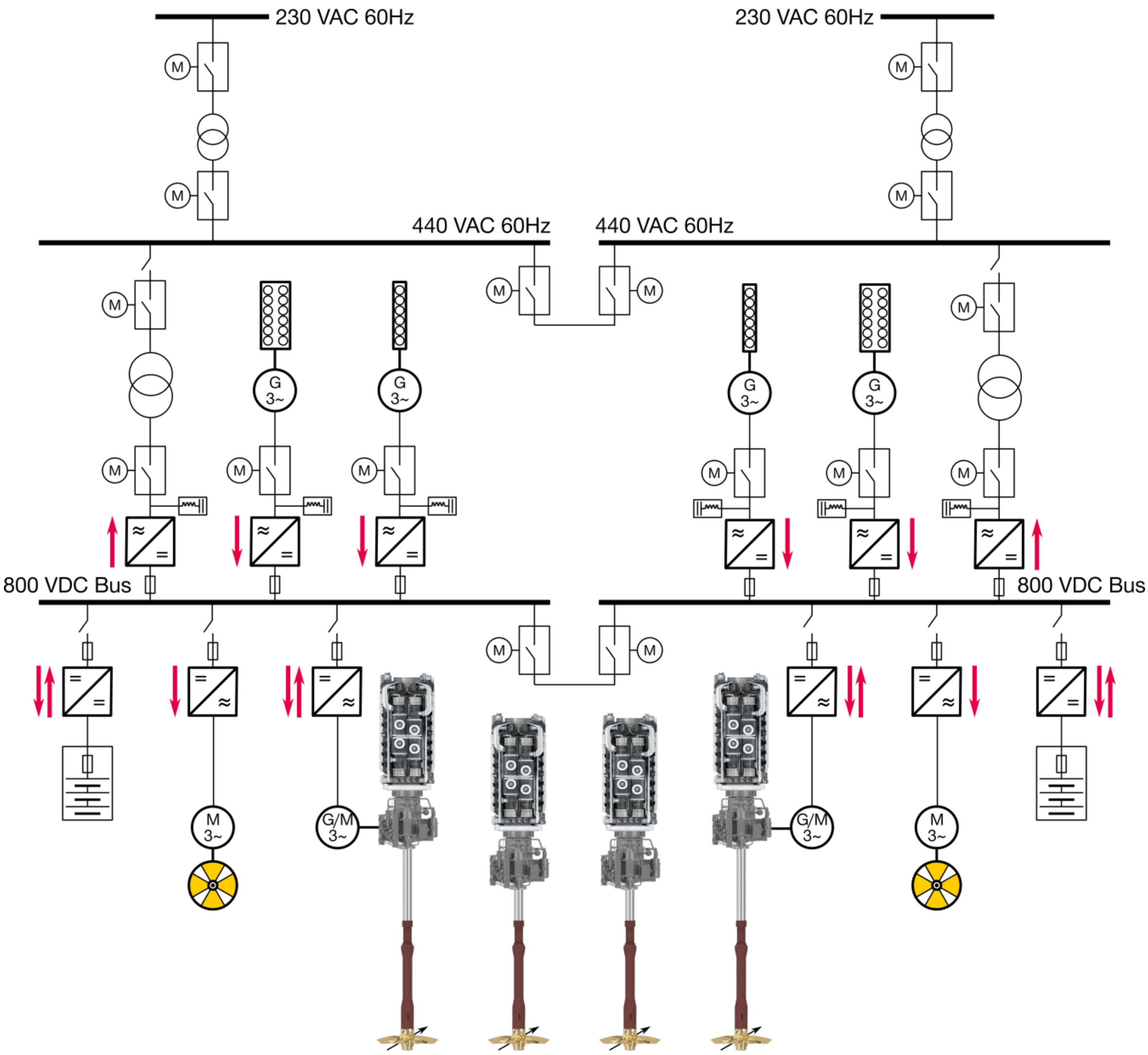


Figure 5 – Conceptual layout of propulsion and power distribution system

This layout has several advantages:

- prime movers are physically independent, providing a high level of redundancy and survivability;
- combining four CP propellers and bow thrusters allows maximum maneuverability;
- electric motors can be operated as shaft generators, reducing the amount of running equipment, increasing the overall fuel efficiency and reducing emission levels;

- the usage of battery banks provides the capability of running in full-electric mode, eliminating both the emission footprint and the risk of running internal combustion engines in dangerous environments;
- the propulsion system has intrinsic reliability during critical operations, without the need for additional sources of uninterruptible power supply (UPS);
- battery banks also act as "peak-shavers" guaranteeing a good load response while avoiding power fluctuations on the diesel engines, therefore improving fuel consumption and eliminating excessive wear;
- feathered CP propellers have minimal impact on ship resistance and impose no operational constraints.

Reference operating modes and profiles.

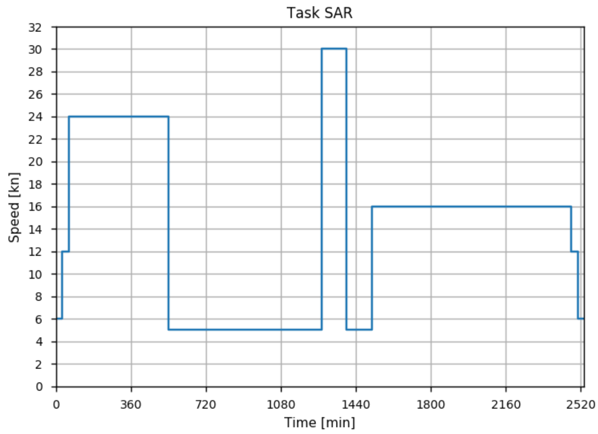
As mentioned above, a detailed definition of vessel operating modes is critical for a successful propulsion plant design and optimization. In real life this is usually confidential information, provided as an input either by the Naval Authority or by the Prime Contractor. For this study four typical missions of second-line naval vessels have been used. They are presented in Table 2 in combination with their time share in a year operation, assumed to be 2000 running hours. Table 3 present the tasks (modes) within the missions, while the definition of each mission is summarized in figures 6 to 9.

Mission name	Time Share
Search & Rescue (SAR)	50%
Emergency Response (ER)	5%
Fishery protection (FP)	25%
Special operations (SO)	20%
Total	100%

Table 2 – Mission & time share in a year of operation

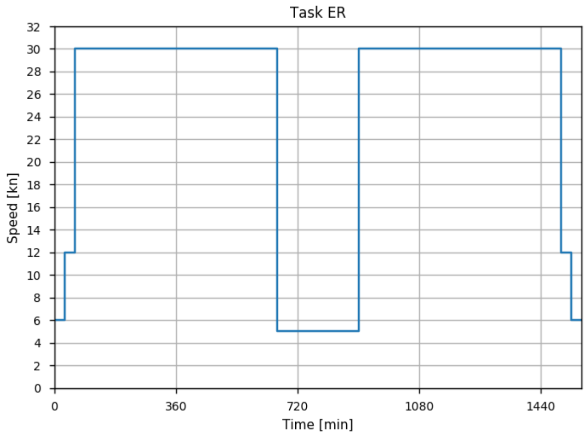
Operating mode	Description	Speed (kn)	Total Time Share
I	Maneuver	6	1.5%
II	Departure/Approach	12	1.5%
III	Patrol	12	22%
IV	Loiter	5	39%
V	Cruise	16	19%
VI	Transfer	24	10%
VII	Fast deploy	30	7%

Table 3 – Operating modes definitions



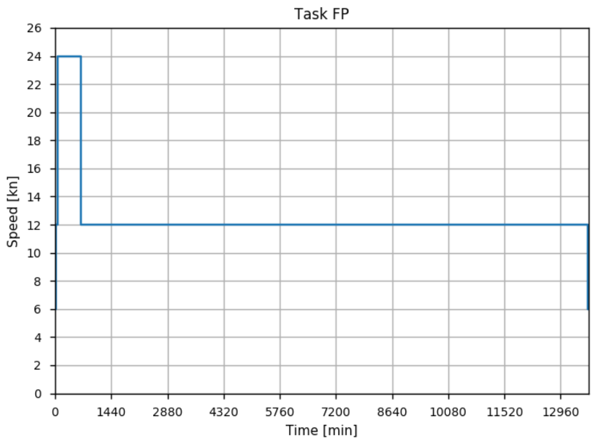
Ident	Mission: Patrol + Search & Rescue	Duration (hrs)	speed (kn)
I	Maneuvering	0,5	6
II	Departure	8,0	12
VI	Transfer	12,3	24
IV	Loitering	2,0	5
VII	Fast Deploy	2,0	30
IV	Loitering	16,0	5
V	Cruise	0,5	16
II	Approach	0,5	12
I	Maneuvering	0,5	6
	Total Mission Time	42,3	

Figure 6 – Mission profile Search & Rescue



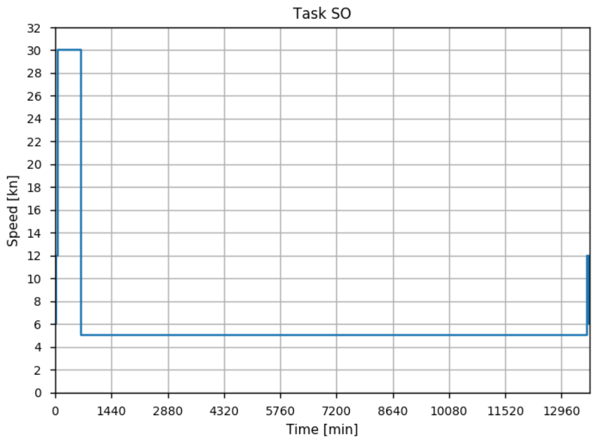
Ident	Mission: Emergency Relief	Duration (hrs)	speed (kn)
I	Maneuvering	0,5	6
II	Departure	0,5	12
VII	Fast Deploy	10,0	30
IV	Loitering	4,0	5
VII	Fast Deploy	10,0	30
II	Approach	0,5	12
I	Maneuvering	0,5	6
	Total Mission Time	26,0	

Figure 7 – Mission profile Emergency Response



Ident	Mission: Special Operations	Duration (hrs)	speed (kn)
I	Maneuvering	0,5	6
II	Departure	0,5	12
VII	Fast Deploy	10,0	30
IV	Loitering	216,0	5
II	Approach	0,5	12
I	Maneuvering	0,5	6
	Total Mission Time	228	

Figure 8 – Mission profile Fishery Protection



Ident	Mission: Fishery Protection	Duration (hrs)	speed (kn)
I	Maneuvering	0,5	6
II	Departure	0,5	12
VI	Transfer	8,0	24
III	Patrol	216,0	12
II	Approach	0,5	12
I	Maneuvering	0,5	6
	Total Mission Time	226,0	

Figure 9 – Mission profile Special Operations

Even if this deterministic approach has been extensively adopted in traditional design, due to the increased availability of real life operating data, statistical approaches, as described in [1] and [2], have been recently favored. It should anyway be noted that the methodology used to describe the operating profile is uninfluential to the propulsion design optimization process, therefore, the traditional deterministic description has been used in this case study to avoid useless complexity.

In general terms the choice of components of a hybrid propulsion system can be treated as a multi-objective design optimization problem. In contrast with traditional propulsion plants which can only be optimized on single operating points, the combination of elements in a hybrid system can be benchmarked across several criteria to find solutions with the best overall trade-off.

Both the objectives and their relative weights can be defined based on project-specific requirements and are usually complemented with additional constraints in order to limit the search to reasonable solutions.

Constraints translate technical and commercial limitations such as:

- rated power of diesel engines, available only in discrete steps according to ratings;
- power of variable frequency drives and electric motor as well as capacity of battery banks, limited by available space and vessel displacement;
- overall or individual cap on acquisition costs.

The investigation produces a set of optimized solutions. In order to fix a single design a final evaluation round is therefore needed. This step should include additional aspects which are difficult to formally be fixed in the initial phase, such as experience on former plants, technological and commercial risk evaluation for certain components, customer preference and so on.

Extensive and advanced work has already been done in such a field and several examples of design optimization algorithms such as [3], [4] and [5] are available in the technical literature.

The case study here presented is based on a calculation workflow internally established at MAN Diesel & Turbo, with the following exemplary set of objectives:

- minimum number of running engines in each operating mode;
- full-electric loitering (mode III) capability for not less than 30 minutes;
- optimum main engine load, according to rating selection;
- optimum auxiliary engine load (range 50%-100%);
- maximum continuous speed not below 32 kn;
- maximum peak speed not below 33 kn.

Additionally the search was restricted to take into account the following constraints:

- main engines according to rating availability as shown in Table 4;
- auxiliary engines according to market availability;
- power of electric motor not exceeding 1 MW and capacity of battery banks not exceeding 300 kWh, in order to limit the volume of frequency drives and switchboards.
- effect of aging of battery elements.

Rating	Rated Power 12V (kW)	Rated Power 16V (kW)	Optimum load range
Heavy Duty (145 kW/cyl)	1740	2320	60%-100%
Heavy Duty (155 kW/cyl)	1860	2480	60%-100%
Medium Duty (170 kW/cyl)	2040	2720	40%-80%
Medium Duty (185 kW/cyl)	2220	2960	40%-80%

Table 4 – MAN 175D rating overview

RESULT OF CALCULATION

For the above scenario the calculated optimal arrangement is summarized in Table 5.

Equipment	Qty	Type	Power/Energy	rpm
Main Engine	2	16V175MM, Medium Duty Optimum load range: 50%-80%	2 x 2720 kW	1900
Booster Engines	2	16V175MM, Medium Duty Optimum load range: 50%-80%	2 x 2960 kW	1900
Gear box Main Engines	2	Single reduction, with PTI/PT0, ratio 3.25		585
Gear box Booster Engines	2	Single reduction, ratio 3.435		553
Main Propeller	2	VBS600 Mk5 A – CPP Prop. Diameter: 1650mm	2 x 3600 kW	585
Booster Propeller	2	VBS540 MK5 A – CPP Prop. Diameter: 1650mm	2 x 3000 kW	585
Battery Pack	2	Li-ion, 6C/3C Charge/Discharge rates, water cooled	2x 500 kWh	
PTO/PTI	2	Power factor cos(phi): up to 0,8	2 x 850 kW	Up to 1800

VSD	2	Low Harmonic AFE converter for PTO and PTI	2 x 850 kW	
GenSet	2	MAN D2862 LE322, 12Cyl	2 x 700 kW	1800rpm
GenSet	2	MAN D 2866 LE301, 6Cyl	2 x 280 kW	1800rpm

Table 5 – Configuration of calculated optimal propulsion layout

The benefits of such a configuration can be assessed by briefly analyzing the performance at different operating modes.

Mode I (Maneuver)

As expected from the figures in Table 3, due to the minimal time share, an optimization in terms of fuel consumption is not significant for this mode. However this mode is mainly performed in harbors, restricted or enclosed waters, where nowadays national maritime and port authorities have engaged in efforts to reduce emissions from all operating vessels within their jurisdiction.

The selected equipment therefore allows maneuvering as well as docking/undocking to be fully conducted in electrical mode meeting even the most stringent regulations.

Additionally the immediate energy availability from the battery packs and the use of variable speed motors provide the vessel with a very high level of maneuverability and agility.

The system operation schematic is presented in Figure 10.

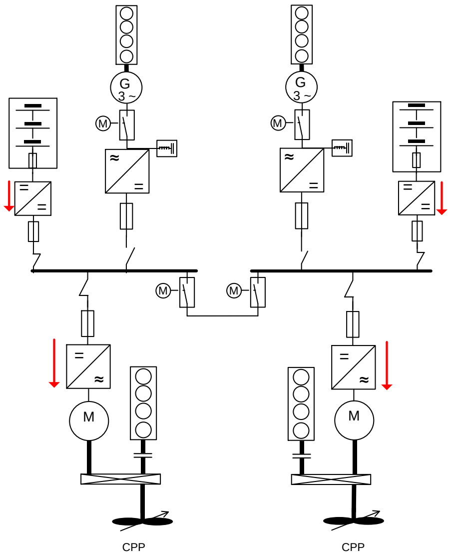


Figure 10 – Operation schematics for Mode I

Mode II (Patrol, Approach & Departing)

A traditional weak spot of conventional propulsion plant, this mode usually requires a single shaft operation to avoid extremely low loads on propulsion engines. This condition has significant drawbacks in terms of maneuverability and response time in case of sudden power request.

The proposed plant overcomes all these limitations, allowing a single diesel propulsion engine to mechanically drive one propeller shaft while providing electric power for both the vessel electric load and the electric motor on the other propeller shaft. This setup, unique to hybrid plants, is conceptually equivalent to a cross-connected gearbox and puts no limitations to vessel capability while minimizing the amount of running equipment and ensuring an efficient engine operating point. Additionally variating the engines speed the propellers can be driven on their efficient combinator curves with evident benefits in term of maneuverability and efficiency.

In this mode batteries can be used as a power reserve, either to compensate wind and current effects, to reach short-term speed peaks or to give a smooth transition to other operating modes.

The system operation schematic is presented in Figure 11.

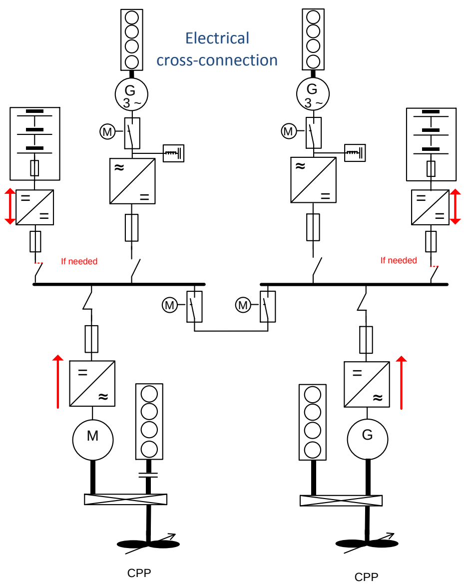


Figure 11 - Operation schematics for Mode II

Mode III (Loiter)

Accounting for almost 40% of the total operating time, performance during loitering is essential for a successful design. With the selected equipment configuration a single genset is used to power to both the electric propulsion motors as well as the power distribution network.

While the advantage over traditional mechanical propulsion plant is evident, this mode also proves itself an excellent example of application on battery-hybrid systems. In loiter mode, due to minimal speed, a major share of power demand is dedicated to vessel own electrical consumption. For a multi-purpose vessel such as the one being considered, this includes also equipment dedicated to cargo handling and special operations, typically highly variable in time. With conventional electric plant, this variability requires several gensets to operate in parallel to avoid the drawbacks of sudden load peaks, such as mechanical wear and reduced reliability with higher risk of blackout, while a battery-hybrid system is simply inherently able to cope with this operation mode without additional effort.

The use of electrical motors allows to move the propellers on their efficient combinator curves with evident benefits in the vessel maneuverability and efficiency.

According to the set objective, full-electric loitering mode with full hotel load is achieved in excess of 30 minutes.

Mode IV (Cruise) and V (Transfer)

Cruise and transfer speeds are achieved by only using the outer diesel engines, while operating the electric motors as shaft generators, thus with no genset running. This outcome is strictly related to the set of objectives as we explicitly searched for solutions to minimize the amount of running equipment.

As discussed above, even if batteries are not directly used they still provide Peak Shaving and Dynamic Support capabilities, with significant performance and reliability boosts in rough sea conditions.

Mode VI (Fast Deploy)

A speed of 30 knots can be reached by using all four diesel engines, with electrical motors operating as shaft generators, therefore keeping the gensets off.

A continuative max speed of above 33 knots is achievable by turning on gensets and using the electric motors as boosters. Even if not perfectly fuel efficient, this layout provides additional flexibility and enables the usage of battery banks as a power reserve, as discussed above.

SUMMARY AND FUTURE DEVELOPMENTS

As shown in the body of the paper, hybrid systems are quickly taking hold in naval designs. By properly selecting and integrating different technologies and including battery banks, it is possible to design solutions optimized for specific requirements.

A practical approach to mission-centric plant design has been shown in the presented exemplary case study and has already been applied to real projects. It is sufficient to observe the quick changes happening in other markets to understand that we are just scratching the surface and the real potential of this technology has still to come.

On the short term DC grids are expected to expand at the expense of traditional AC distribution systems, allowing easier integration of battery banks and usage of variable speed gensets and induction propulsion motors.

In contrast with the traditional fixed speed concept, variable speed gensets can be adjusted for minimum fuel oil consumption according to the system load. The DC grid allows a decoupled operation of the gensets for the consumers and also allows the easy integration of batteries via DC/DC converters. The footprint of such a propulsion plant is up to 25% smaller compared with a classical Diesel-electric propulsion plant based on an AC system.

The DC architecture allows also the usage of induction motors in place of the traditional synchronous machines. Induction motors are cheaper, simpler and more robust machines which can significantly reduce acquisition costs, nowadays the major obstacle to hybrid market diffusion.

Finally DC systems are core technology for leading markets, the automotive one above all, and will therefore benefit the big innovation wave already ongoing, including more sophisticated developments such as autonomous and unmanned operation, currently being investigated also in the marine market.

Even if marine and naval markets have their own specificity, they will definitely be affected by this global trend, therefore battery-hybrid systems can be reasonably considered to stay in the spotlight and gain momentum for the years to come.

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