

Design and control of hybrid power and propulsion systems for smart ships
A review of developments

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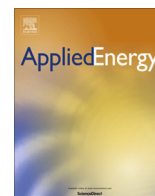
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Design and control of hybrid power and propulsion systems for smart ships: A review of developments



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HIGHLIGHTS

- Classifies mechanical, electrical and hybrid propulsion for ships.
- Classifies combustion, electrochemical, stored and hybrid power supply for ships.
- Reviews opportunities, challenges and trends for power and propulsion architectures.
- Summarises control strategy developments, their benefits and opportunities.
- Proposes holistic research into torque, pitch, and model predictive control.

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ABSTRACT

The recent trend to design more efficient and versatile ships has increased the variety in hybrid propulsion and power supply architectures. In order to improve performance with these architectures, intelligent control strategies are required, while mostly conventional control strategies are applied currently. First, this paper classifies ship propulsion topologies into mechanical, electrical and hybrid propulsion, and power supply topologies into combustion, electrochemical, stored and hybrid power supply. Then, we review developments in propulsion and power supply systems and their control strategies, to subsequently discuss opportunities and challenges for these systems and the associated control. We conclude that hybrid architectures with advanced control strategies can reduce fuel consumption and emissions up to 10–35%, while improving noise, maintainability, manoeuvrability and comfort. Subsequently, the paper summarises the benefits and drawbacks, and trends in application of propulsion and power supply technologies, and it reviews the applicability and benefits of promising advanced control strategies. Finally, the paper analyses which control strategies can improve performance of hybrid systems for future smart and autonomous ships and concludes that a combination of torque, angle of attack, and Model Predictive Control with dynamic settings could improve performance of future smart and more autonomous ships.

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1. Introduction

The shipping industry, like many other industries, is under great pressure to reduce its environmental impact. If no measures are taken, CO₂ emissions are projected to increase 50–250% by 2050, while the Paris convention requires a significant reduction to

achieve the 2 °C global warming target [1]. Moreover, shipping already contributes to 15% of the global NO_x emissions, which is also projected to increase if no measures were taken [1]. Advances in power and propulsion systems and energy management improvements, however, can significantly contribute to reducing both CO₂ and NO_x emissions [2].

To enforce these advances, the International Maritime Organization (IMO) Marpol regulations impose increasingly stringent restrictions on ship's emissions [3]. First, IMO Marpol annex VI sets limitations on the weighted cycle nitrogen oxide (NO_x) emissions for diesel engines with an output of more than 130 kW. For example, diesel engines on ships constructed after January 2011, referred to as Tier 2, are limited to 7.7 g/kWh for high speed engines and 14.4 g/kWh for very low speed engines. In emission control areas, from January 2016, referred to as Tier 3, these limits reduce to 2.0 g/kWh and 3.4 g/kWh [3]. These limits currently address the NO_x production of engines and not of the ship propulsion and power generation as a whole. However, developments to address NO_x production per mile for cars and the public outcry to determine standards in realistic driving conditions, might lead to future shipping regulations limiting the production of NO_x per mile [4]. Nevertheless, the most important research area to reduce NO_x emission from propulsion and power generation of diesel engines are NO_x abatement technologies such as Exhaust Gas Recirculation (EGR) and Selective Catalytic Reduction aftertreatment (SCR) [5–7]. Secondly, IMO Marpol regulations have set targets for reducing the Energy Efficiency Design Index (EEDI) for new ships. This EEDI is a measure of the amount of CO_2 emissions that a cargo ship produces per tonne of goods and per mile. New cargo ships have to reduce their EEDI from 10%, compared to benchmark cargo ships at the introduction in 2013, to 30%, in 2030. Similar measures are being prepared for other ship types. Therefore, the propulsion and power generation plants for future ships have to significantly reduce fuel consumption and emissions over the coming years.

While the pressure to reduce fuel consumption and emissions has increased, the operating profile of ships has become increasingly diverse: offshore vessels perform numerous tasks, such as transit and critical dynamic positioning (DP) operations [8,9]; heavy crane vessels, such as the *Pioneering Spirit*, exhibit an increased capacity and complexity for diverse offshore operations; naval ships perform traditional patrol operations in open sea, but are also deployed in littoral operations; and tugs require full bollard pull when towing and require limited power during transit or standby [10]. Due to these diverse operating profiles, the power and propulsion plant has to perform well on many performance criteria, such as:

1. Fuel consumption;
2. Emissions;
3. Radiated noise;
4. Propulsion availability;
5. Manoeuvrability;
6. Comfort due to minimal noise, vibrations and smell;
7. Maintenance cost due to engine thermal and mechanical loading; and
8. Purchase cost.

Furthermore, the diverse operational profile makes it hard to optimise the power and propulsion plant for a specific operating point at a vessel's design stage, as was conventionally done. Thus, since the 1990s, the power and propulsion configuration has been adapted to a varied operating profile with electric propulsion for various ship types, such as cruise ships and capital ships, like *HNLMs Rotterdam* (see Fig. 1). However, although electrical propulsion is more efficient at low speed, it introduces additional conversion losses of 5–15% of the propulsive power in electrical components such as generators, power converters, transformers and electric motors.

This trade-off between efficiency and adaptability to diverse operating profiles has led to a growing variety of power and propulsion architectures, which can be categorised as follows:



Fig. 1. HNLMS Rotterdam with electric propulsion.

- Mechanical propulsion, electrical propulsion or a hybrid combination of both;
- Power generation with combustion engines, fuel cells, energy storage or a hybrid combination; and
- AC or DC electrical distribution.

As complexity of the system architecture increases, the degrees of freedom in control increase. However, most advanced propulsion architectures still use the same traditional control strategies: fixed combinator curves, fixed frequency generators, rule-based use of batteries and operator-controlled configuration settings. Conversely, research in the maritime and automotive domain has shown that advanced architectures with traditional control do not significantly reduce fuel consumption or emissions while cost and complexity of the system do increase [10,11].

Nevertheless, advanced control strategies for maritime applications have hardly been developed yet. The limited research in optimisation of battery deployment and intelligent use of DC architectures has, however, shown that smart control strategies can deliver reductions of 10–35% in fuel consumption and emissions [12–18]. Analysis of the impact on other criteria has hardly been covered. Therefore, holistic research into and development of smart control strategies to improve performance on various criteria is urgently required to achieve the benefits of advanced architectures for future smart ships. In order to direct this research, applicable control strategies have to be reviewed for each architecture, as well as their performance on the criteria listed above.

While extensive reviews are available on automotive hybrid electric vehicle architectures and their control strategies [19,11,20,21], such a review is lacking on power and propulsion architectures for ships and their control strategies. Moreover, the classification in parallel, series and series-parallel [19,22] hybrid electric vehicles does not apply to ship's power and propulsion architectures, as ships can have multiple propulsion engines, electric propulsion motors, diesel generators, fuel cells and energy storage systems. Therefore, this paper provides a survey of the development and application of hybrid power and propulsion architectures and their control strategies for ships. The paper classifies the propulsion topology into mechanical propulsion (Section 2), electrical propulsion (Section 3) and hybrid propulsion (Section 4) and the power system topology in combustion power supply, electrochemical power supply, stored power supply and hybrid power supply (Section 5). Moreover, the paper reviews combined architectures, such as hybrid propulsion with hybrid power supply (Section 6) and hybrid propulsion with DC hybrid

power supply (Section 7). For all these power and propulsion architectures, the paper reviews the benefits and challenges, the application on ships and the control strategies. Because research on these advanced architectures and control strategies for ships is limited, each section also reviews relevant literature from terrestrial microgrid and hybrid electrical vehicle technology. Finally, the paper summarises the developments, benefits, drawbacks and application trends of the power and propulsion system architectures, and reviews the available control strategies and their benefits in Section 8, reviews the research opportunities in Section 9 and concludes in Section 10.

2. Mechanical propulsion

Prior to the 19th century, ships were propelled by oars and sails. Then, the development of the steam engine led to the introduction of mechanical propulsion. Over the 19th and 20th centuries, the driving engines developed from reciprocal steam engines and steam turbines into diesel engines and, for some applications, gas turbines. A detailed historical review of these developments can be found in Curley [23].

A typical architecture for a modern ship with mechanical propulsion is presented in Fig. 2. A prime mover (1), typically a diesel engine or gas turbine, drives the propulsor (3), typically a propeller, either directly or through a gearbox (2). Alternative prime movers are steam turbines in combination with a (nuclear) steam raising plant and gas turbines. However, this review focuses on diesel engines, as most ships use them due to their high fuel efficiency.

A separate electrical AC network (6) is required for generating and distributing electric power of auxiliary loads (5), such as variable speed drives (4), heating ventilation and air-conditioning (HVAC) and other mission-critical and auxiliary systems. Diesel, steam-turbine or gas-turbine generators (7) feed this electrical network.

For large cargo ships, driven by low speed diesel engines, no gearbox is required and reversing can be achieved by reversing engine rotation. On the other hand, smaller ships do require a gearbox to reduce the engine speed, as they are driven by medium- or

high-speed diesel engines. This gearbox can also be used for reversing shaft rotation.

The most applied propulsor is a Fixed Pitch Propeller (FPP). It requires a reversible engine or gearbox for stopping and reversing. Alternatively, a controllable pitch propeller (CPP) can provide negative thrust for stopping and reversing. Other propulsors are water jets, surface piercing propellers, cycloidal propellers, paddle wheels, whale-tails, and magneto hydrodynamic propulsion [24]. Furthermore, propulsion and steering can be combined in steerable thrusters. This review, however, will be limited to propellers, although the same principles and control strategies apply to other propulsors as well. Therefore, the characteristics of the FPP and CPP will be introduced next in more detail.

2.1. Fixed pitch propeller

When the propulsor in a mechanical propulsion plant is an FPP, the ship's resistance, propeller and gearbox determine the load characteristic of the diesel engine. This load characteristic is referred to as the *propeller curve* [25]. In Fig. 3, three propeller curves have been plotted, representing the load experienced by the diesel engine in trial condition, design condition, and off-design condition [26].

The propeller curves have been plotted in the *engine operating envelope*. This operating envelope shows the maximum power the engine can deliver as a function of engine speed. Moreover, Fig. 3 shows the specific fuel consumption (SFC) of the engine as a function of engine speed and delivered power. This specific plot is derived from a quadratic fit model of a typical medium speed diesel engine.

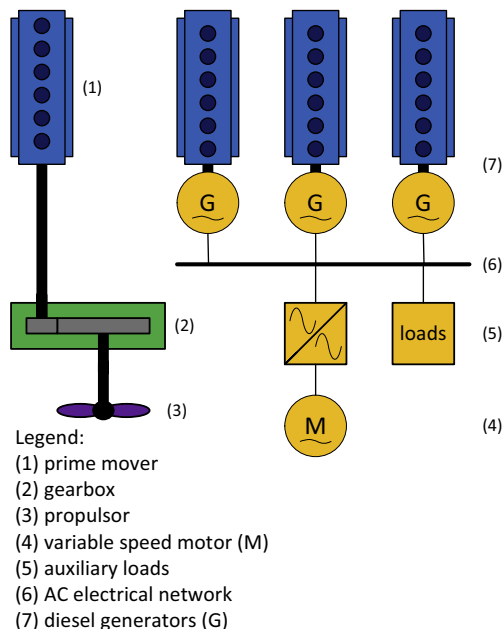


Fig. 2. Typical mechanical propulsion system.

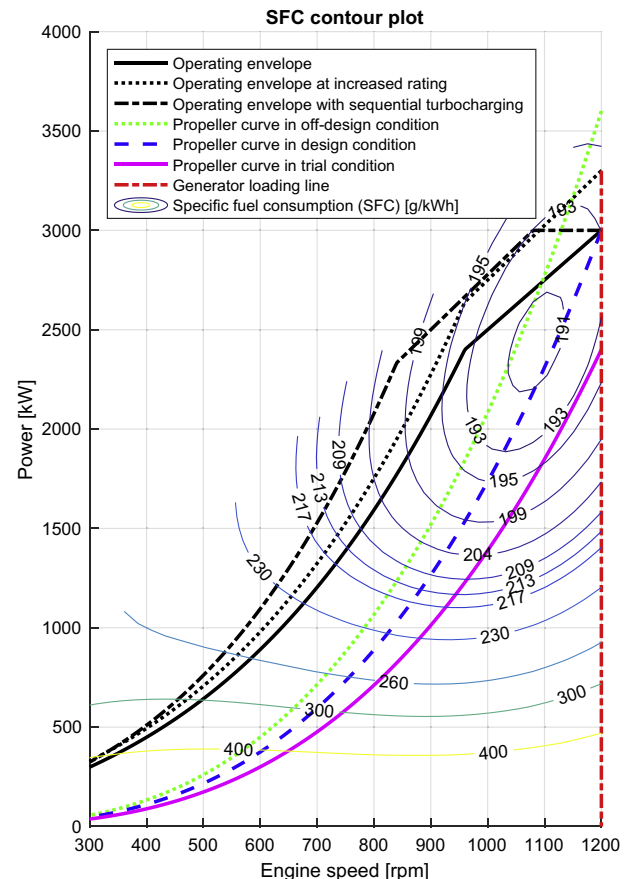


Fig. 3. Three propeller curves and the generator loading line in three diesel engine operating envelopes with typical SFC contour plot.

The propeller curves, operating envelope, and SFC contour plot represent stationary conditions, without acceleration and deceleration. When operating in stationary conditions, the diesel engine delivers a constant power output at a constant engine speed. For example, the design speed could be achieved in the operating point at 1125 rpm and 2500 kW. At this design condition, the specific fuel consumption is 191 g/kWh. On the other hand, in the off-design condition due to heavy weather and hull fouling, the design speed will be achieved in the operating point at 1125 rpm and 3000 kW, leading to an average specific fuel consumption of 193 g/kWh.

However, in dynamic conditions, such as sailing in heavy weather and turning, the actual load fluctuates around the average operating point of the propeller curve [27,28]. The off-design condition shown in Fig. 3 represents the average increase in load. In order to prevent overloading from the fluctuation around the average load, sufficient margin between the propeller curve and the engine operating-envelope is required. This can be achieved by selecting an engine with an increased rating (see Fig. 3).

However, an overrated engine increases the cost of the propulsion plant and increases fuel consumption as the average operating point may now have a greater distance from the optimal fuel consumption, which is close to the maximum loading line. Alternatively, selecting an engine with a broader operating envelope in part load has recently become possible. A broader operating envelope can be achieved with sequential turbocharging, a waste gate, or variable turbine geometry [25]. For instance, sequential turbocharging (STC) widens the operating envelope by switching off a turbocharger when exhaust gas flow is too low for effective performance.

In conclusion, the challenge with an FPP is to match the diesel engine, gearbox, propeller and ship's resistance, so that the engine can run safely within its operating envelope across the speed range of the engine. The minimum speed of the ship is limited by the minimum engine speed limit. For reversing, either the engine or the gearbox needs to be reversible.

2.2. Controllable pitch propeller

To overcome the challenges mentioned above, a CPP can be used [25], because propeller pitch introduces an additional degree of control. Reducing the pitch reduces propeller thrust, and the power absorbed by the engine at a certain shaft speed. This allows the thrust to be reduced below the value of minimum engine speed and full pitch. Moreover, reversing pitch enables the thrust to be reversed without reversing the engine or gearbox. CPP thus directly improves manoeuvrability and the control strategy can be used to improve performance.

2.3. Benefits and challenges of mechanical propulsion

Mechanical propulsion is particularly efficient at design speed, between 80 and 100% of top speed. In this range the diesel engine operates in its most efficient working point (see Fig. 3). Moreover, mechanical propulsion consists of only three power conversion stages, the main engine, the gearbox and the propeller, which leads to low conversion losses. Because the limitations on NO_x emissions for Tier II and Tier III engines are expressed in g/kWh, efficient operation, leading to lower power output, will also lead to lower NO_x emission, bearing in mind that the limitations for high speed engines are lower than those for low speed engines. Finally, the purchase cost of mechanical propulsion is low, due to its low complexity. This justifies the application of mechanical propulsion for transport ships, as illustrated with the energy analysis performed on a deadweight tanker, which converts 88% of its energy in the main diesel engines [29]. This study thus concludes that, for these

ship types, fuel consumption and emissions can best be reduced by recovering waste heat in exhaust gas and cooling water to generate auxiliary electrical power and heating.

However, matching the engine for the design speed also fixes plant behaviour for the rest of the operating envelope. A CPP can add an additional freedom of control at the cost of increased system complexity. Nevertheless, mechanical propulsion faces the following challenges:

- The manoeuvrability is limited by the engine's operating envelope. Manoeuvrability can be improved with CPP but remains limited to prevent engine overloading.
- High static and dynamic engine loading can increase the required maintenance effort for the engine. Application of CPP with an appropriate control strategy can reduce static and dynamic loading [26,30,28].
- Mechanical propulsion has a poor fuel efficiency and high emissions when sailing at speeds below 70% of top speed, because engine fuel consumption significantly increases below 50% of rated power (see Fig. 3).
- Mechanical propulsion exhibits poor availability, because failure of any of the components in the drive train directly leads to loss of propulsion.
- The NO_x emissions of the main propulsion engine are determined by its operating points in the operating envelope. In automotive, diesel engine research has shown that the NO_x emissions during the world-harmonized light-duty vehicle test cycle (WLTC), with increased acceleration profile, are much higher than the current Euro 6 standard of 80 mg/km, which is assessed in the new European driving cycle (NEDC) with more constant loading [4]. This trend is confirmed by NO_x measurements performed on a 300 kW MAN4L20/27 research engine without NO_x abatement technology at the Netherlands Defence Academy shown in Fig. 4, from Linden [31]. Similarly, diesel mechanical propulsion during acceleration is likely to lead to high NO_x emissions due to the high cylinder temperature caused by the turbolag. NO_x emissions for ships in this situation are likely to occur at a higher rate in g/kWh than the specified Tier 2 or Tier 3 standard.
- The radiated noise performance is limited due to the mechanical transmission path from the engine to the propeller, although isolation measures can improve this.

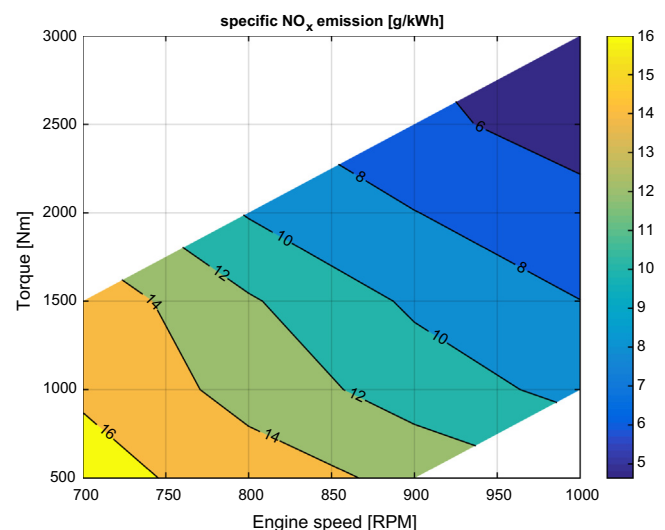


Fig. 4. NO_x measurement results of MAN4L20/27 research engine on Netherlands Defence Academy in contour plot, from Linden [31].

- Radiated noise performance due to cavitation is limited, particularly in dynamic conditions, but can be improved with CPP and a proper control strategy [27].

The control strategies for mechanical propulsion should be aimed at addressing these challenges.

2.4. Application of mechanical propulsion

After the introduction of the steam engine, most ships used mechanical propulsion. In order to meet the challenges listed above, various electrical architectures have replaced purely mechanical propulsion for many applications. However, mechanical propulsion remains the preferred architecture for ships that sail at a single cruise speed most of the time, because its fuel efficiency at full load is high. Examples of such ship types are cargo ships and fast crew suppliers.

With mechanical propulsion, other ship types would operate at low power in the operating envelope of the engine in certain operating modes. For example tugs only require 20% of their maximum power required for towing during transit, and offshore vessels operate at very low power during DP. For these ship types, mechanical propulsion would lead to poor specific fuel consumption and high emissions. Thus, electric or hybrid propulsion could be considered to improve part-load fuel efficiency. Nevertheless, over 50% of tugs operating around the globe consist of mechanical propulsion.

Alternatively, ships with a limited number of distinct operating modes can benefit from mechanical propulsion with multiple shafts and/ or multiple engines on one shaft, through a gearbox with clutches. These engines can be of the same type or of different types. Such configurations with multiple engines and shafts can also improve propulsion availability. For example, many naval frigates utilise combined diesel or gas-turbine (CODAG) or combined diesel and gas-turbine (CODAG) propulsion plants. While many European navies and the US Navy in their new designs opt for hybrid or full electric propulsion, many smaller navies still apply mechanical propulsion, even in recent vessels.

Dredging ships currently still mostly apply mechanical propulsion with also a direct mechanical drive on the dredging pumps. Their dynamic operating profile and the arduous dynamic loading of both propulsion and dredging pumps due to inconsistencies in the dredge spoil, are motivations to consider electrical drives for both the dredging pumps and propulsion.

Finally, many yachts consist of mechanical propulsion. An important aspect of yacht design is to achieve the maximum top speed with the smallest possible installed power. The high efficiency of mechanical propulsion at the design point, enables high speed. However, requirements to improve the comfort when sailing at low speeds and improve the flexibility in operation have led to the development of hybrid yacht concepts [32].

2.5. Control strategies for mechanical propulsion

This section covers the control strategies for mechanical propulsion that have been implemented in ships or published in research.

2.5.1. Governor speed control

The standard control strategy for mechanical propulsion with a fixed pitch propeller is to control engine speed as a function of the lever setting. The diesel engine's speed governor typically fulfils this task with a PID controller. Most ships are equipped with a lever that sets the reference speed as a percentage of full speed. Alternatively, the actual reference speed can be entered. Ships can also be controlled with the DP system. Then the DP system

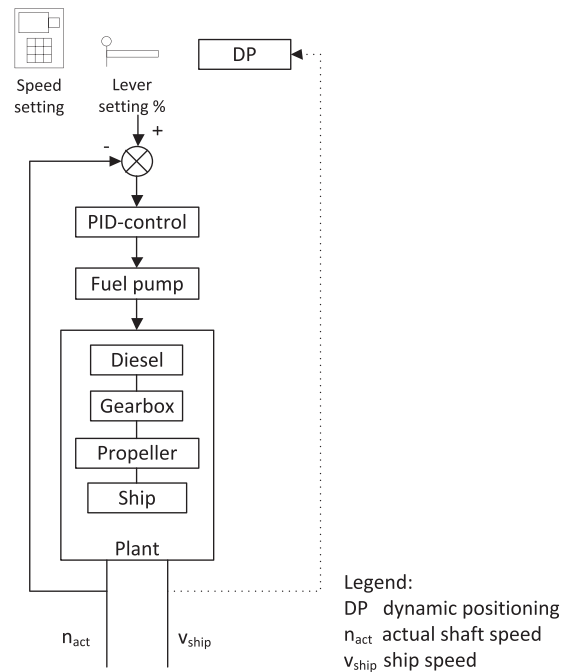


Fig. 5. Control loop for mechanical propulsion with fixed pitch propeller.

generates the actual shaft or engine speed setting. The standard control loop is illustrated in Fig. 5.

Many publications have concluded speed control leads to unnecessary engine load disturbances [27,28,33–35,30]. Faber [33] argues that running the engine with constant fuel injection leads to more constant thermal loading of the engine and better fuel-efficiency. Nevertheless, industry primarily uses speed control, because it provides over-speed protection and a nearly linear relationship between the speed setting and the resulting ship speed.

Xiros [36] proposes a method for robust PID speed governor design that increases load disturbance attenuation compared to traditional PID control. This method utilises the H_∞ norm of the closed-loop transfer function from propeller disturbance to shaft rpm. D-action is required, in order to achieve robust control with higher order dynamical terms. However, it is not possible to directly implement the D-term on the speed feedback signal, due to torque fluctuation from engine and propeller. To overcome this, Xiros proposes predicting the speed derivative from the measured shaft torque and the system dynamics model, thus achieving robust PID H_∞ control that significantly attenuates disturbances due to wind, waves and turns.

2.5.2. State feedback control with engine and turbocharger speed measurement

Xiros [36] also proposes a method for H_∞ state feedback controller synthesis using engine and turbocharger speed as state variables. This allows a single disturbance origin, for example the propeller load. Furthermore, the method allows separate scalar H_∞ norm requirements for the state variables. The schematic representation of state feedback control is illustrated in Fig. 6. The improvements that can be achieved with this method have not been quantified and this needs further research.

2.5.3. Adaptive speed control

When the mechanical propulsion plant consists of a fixed pitch propeller, the freedom of control is limited. Moreover, the speed control loop aims to maintain engine speed, causing considerable

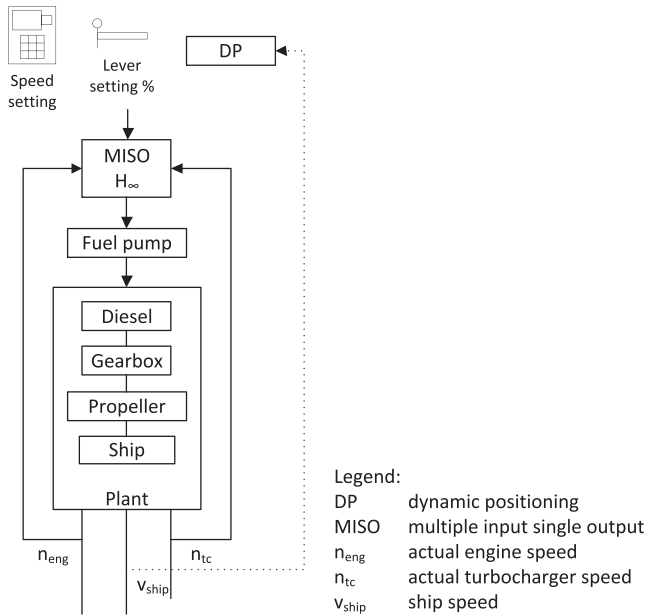


Fig. 6. Control loop for state feedback control.

fluctuation of engine loading during disturbances from waves and manoeuvring [27,28]. Both Royal Netherlands Navy (RNLN) and Canadian frigates with mechanical propulsion have suffered from significant increased maintenance costs due to dynamic engine overloading [28,30].

Guillemette and Bussi eres [30] propose an ‘optimal’ speed controller that adapts the diesel engine speed feedback signal to the governor via an amplifier. It determines the optimum value for this amplifier real-time, with a cost function that trades off future predicted engine speed fluctuation and fuel rack actuation due to predicted engine load disturbance. Current engine load disturbance is estimated using a Kalman filter. Future engine load disturbance is predicted using autocorrelation of statistical data, based on the current estimated load disturbance. Even though the case study has a CPP, pitch is held constant. The work demonstrates that, with maximum cost attributed to fuel rack actuation–counterintuitively–the engine speed fluctuation reduces from the situation with governor speed control. When maximum cost is attributed to engine speed fluctuation, it reduces even further – as expected. However, Guillemette and Bussi eres [30] do not confirm whether the combination of an estimated load disturbance and a predicted future load disturbance using autocorrelation of statistical data can lead to robust control in a practical environment with additional measurement disturbances. The proposed test bed and shipboard trial have not been reported in follow-on publications.

2.5.4. Combinator curve control

The current standard control strategy with a CPP is to determine a fixed *combinator curve*, which sets the relationship between the speed setting from the lever and both propeller pitch and engine speed reference [27]. Propeller pitch and engine speed are controlled in separate control loops, as illustrated in Fig. 7. The combinator curve, shown in Fig. 8, allows: the engine load to be reduced by reducing propeller pitch (area 1); propeller thrust to be controlled below minimum engine speed by reducing propeller pitch at minimum engine speed (area 2); and thrust to be reversed without reversing engine speed (area 3). The associated static engine loading line for this combinator curve is presented in Fig. 9.

The combinator curve as such determines the static operating point of the diesel engine and can be optimised for a number of cri-

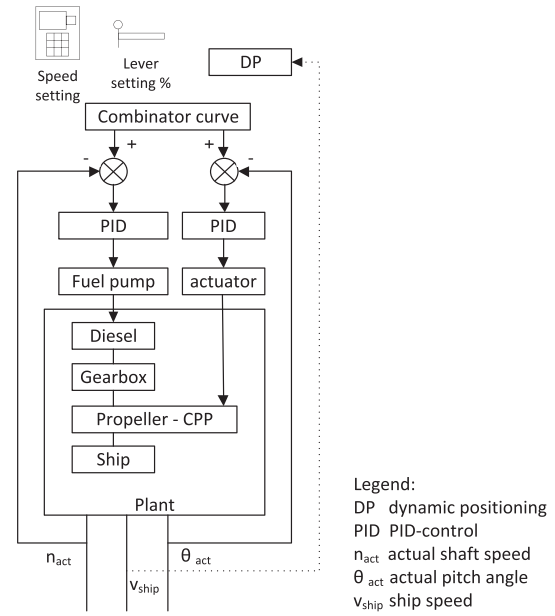
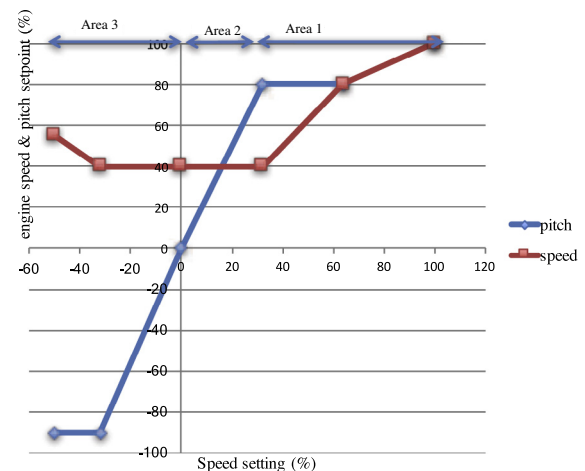


Fig. 7. Control loop for mechanical propulsion with controllable pitch.



Area 1: reduce pitch to reduce engine load
 Area 2: control propeller thrust below minimum engine speed by reducing pitch
 Area 3: reverse thrust without reversing engine speed

Fig. 8. Typical combinator curve.

teria such as fuel efficiency, engine loading and cavitation. However, this average operating point also highly depends on the ship's state (loading, fouling, etc.) and the environmental conditions (wind and sea state). Accordingly, Vrijdag et al. [37] argue that a single fixed combinator curve cannot ensure that engine operation will meet loading and cavitation requirements under all circumstances; they illustrate this with the practical example of a frigate.

This limitation of a single combinator curve has partly been overcome by having a number of static combinator curves for different operating modes of the ship. For example, engine speed is kept low for fuel efficiency in ‘transit’ mode, and engine speed is maintained at a higher value for increased acceleration performance in ‘manoeuvring’ mode. However, this does not account for the impact of changes in ship's state and environmental conditions on the propeller curve, and therefore the plant performance can be poor in certain states and conditions.

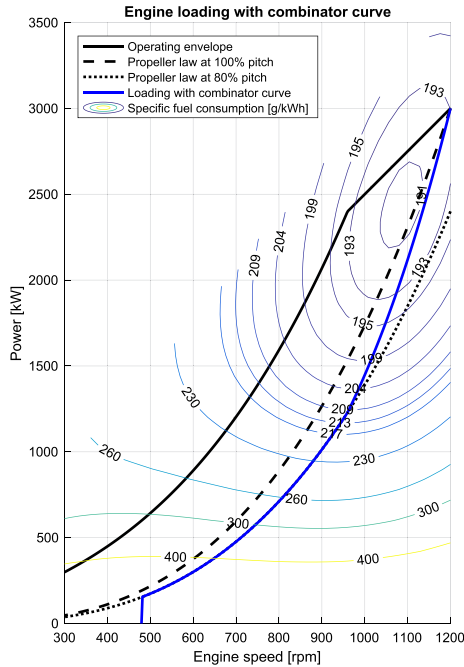


Fig. 9. Engine loading with combinator curve control of Fig. 8.

2.5.5. Combinator curve control with pitch reduction

Another strategy to prevent overloading has been to apply pitch reduction when the engine supersedes the *overloading criterion*, an alternative engine loading limit, comparable to the operating envelop introduced earlier. This approach has been applied to RNLN M-class frigates and Canadian Patrol Frigates [37,30]. Although this strategy effectively prevents overloading, it has a detrimental impact on propulsion performance, particularly on acceleration behaviour [28,30] and cavitation inception [27].

2.5.6. Optimal speed and pitch H_∞ control

The speed regulation control strategy is responsible for the dynamic behaviour of the engine. Fig. 10 shows the fluctuations of fuel rack position and shaft speed as a result of speed regulation as measured on a RNLN M-class frigate, from Van Spronsen and Toussain [28]. In this specific case the engine suffers from overloading, which leads to increased maintenance cost.

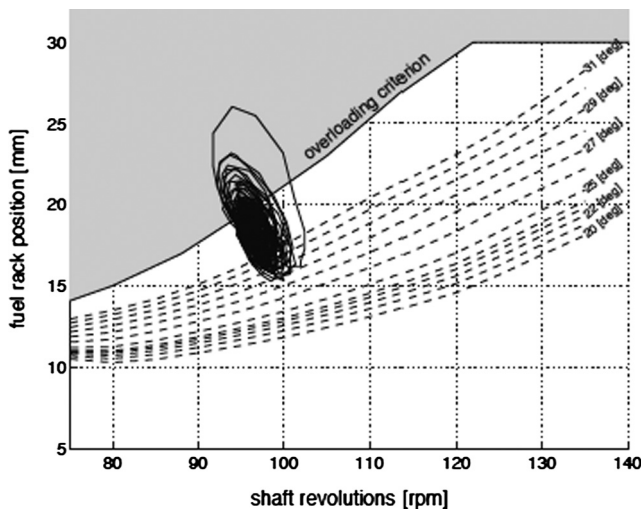


Fig. 10. Dynamic overloading due to sea state plotted in the phase plane.

Van Spronsen and Toussain [28] propose a control strategy that utilises the control inputs engine fuel rack and propeller pitch. They define the control objective to minimise the effect of sea state on engine speed and maximise acceleration and deceleration performance. A constraint is defined to prevent the engine operating in the overloading region, i.e. torque superseding the overloading criterion. A schematic representation of the control loop is presented in Fig. 11.

The proposed multiple input, multiple output H_∞ design achieves a promising control performance that prevents engine overloading while increasing acceleration performance. However, the control strategy is aimed at minimising engine speed fluctuation, and, therefore, causes significant fluctuation of fuel injection and propeller torque. This fluctuating fuel injection causes increased fuel consumption and fluctuating torque increases thermal loading and radiated noise. These effects of minimising engine speed fluctuation are undesirable, while, as argued before, shaft speed fluctuation does not have to be minimised.

2.5.7. Effective angle of attack control

In Vrijdag [27], a control strategy that reduces cavitation in operational conditions is proposed. With this control strategy, propeller pitch is governed to achieve the effective angle of attack at which the chance of cavitation occurring is minimal. This effective angle of attack in essence is the angle at which water flows into the propeller blade profile. The detailed definition is given in Vrijdag [27]. Increasing engine speed to compensate for the reduced pitch due to the control strategy results in the requested virtual shaft, which is defined as follows:

$$n_{virt} = \frac{\theta - \theta_0}{\theta_{nom} - \theta_0} \cdot n$$

where n_{virt} is virtual shaft speed, θ is actual pitch angle, θ_0 is the pitch at which zero thrust is achieved, θ_{nom} is nominal pitch and n is actual shaft speed. The engine speed control loop is retained to allow testing on board a RNLN M-class frigate. The control loop is shown in Fig. 12. On board testing of the control strategy in combination with analysis of simulations has proven that this control strategy reduces cavitation time and - as a side effect - improves acceleration performance, without overloading the engine in trial conditions.

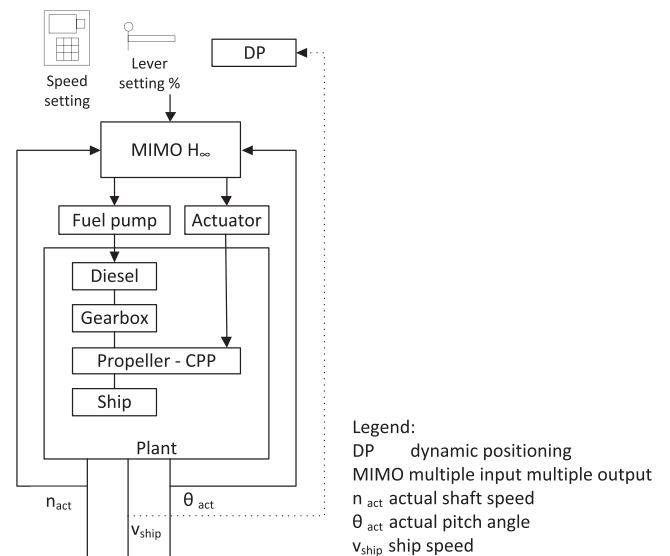


Fig. 11. Control loop for optimal speed and pitch H_∞ control.

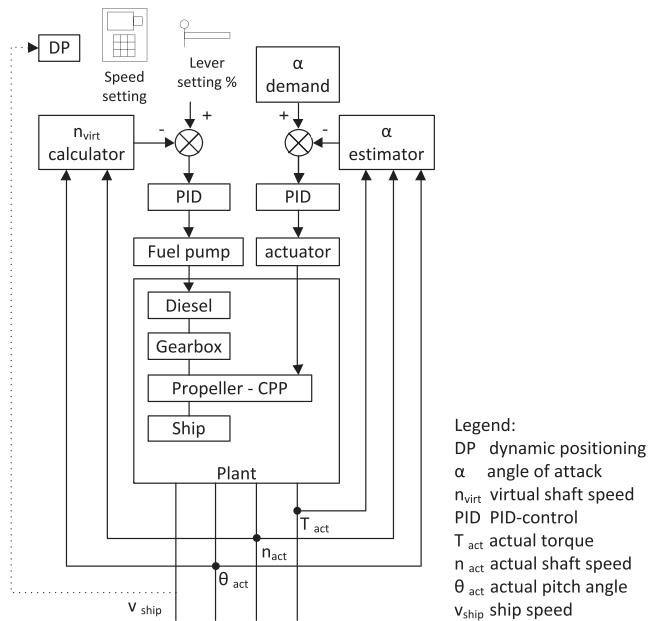


Fig. 12. Control loop for effective angle of attack control.

3. Electrical propulsion

Electrical propulsion has been around since the early 1900s. A short historical review of electrical propulsion is covered in Moreno and Pigazo [38]. In the 1990s, electric propulsion received an enormous boost in the cruise ship industry and in capital naval ships (see Fig. 1). A typical architecture of an electric propulsion system is depicted in Fig. 13. Multiple diesel generator sets (1) feed a fixed frequency high voltage electrical bus (2). This bus feeds the electrical propulsion motor drive (5) and the hotel load (6), in most cases through a transformer (3). The electric propulsion motor drive consists of a power electronic converter (4) used to control shaft line speed and thus ship speed.

3.1. Benefits and challenges of electrical propulsion

In the first place, electric propulsion is a fuel-efficient propulsion solution when the hotel load is a significant fraction of the propulsion power requirement and the operating profile is diverse, because the generator power can be used for both propulsion, through the electric motors, and auxiliary systems [39]. To achieve this, a power management system (PMS) matches the amount of running engines with the required combined propulsion and hotel load power. This control strategy ensures engines do not run inefficiently in part load and is often referred to as the *power station concept*.

Secondly, the NO_x emissions of electric propulsion are likely to be less than those of mechanical propulsion, because the propulsion power at full ship speed is, in most cases, split over more engines, which due to their lower individual power run at a higher speed. For example, a cruise ship with an electrical propulsion power of 20 MW per shaft typically has 5 diesel generators installed, running at 720 rpm, and a cruise ship with a mechanical propulsion plant of 20 MW per shaft typically has two main engines of 20 MW, each running at a maximum speed of 500 rpm with four-stroke diesel engines or 80 rpm with two-stroke engines. For Tier II, this would mean a cycle-averaged NO_x production of 9.7 g/kWh for the diesel generators used in electrical propulsion and of 10.5 or 14.4 g/kWh for the four-stroke or two-stroke diesel engines used in mechanical propulsion. Moreover, due to the

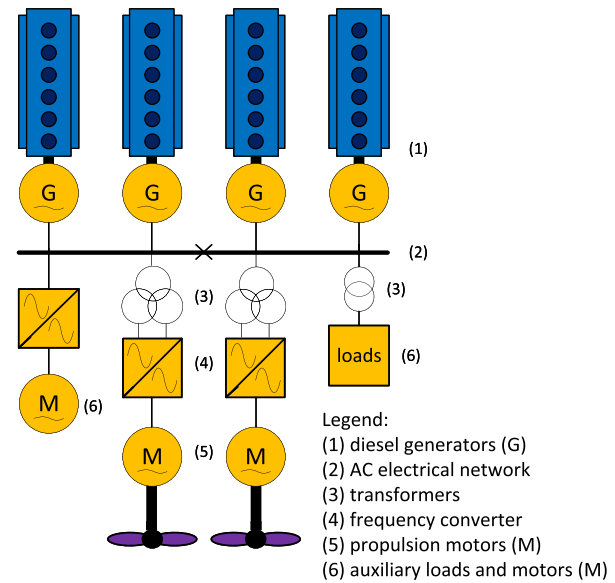


Fig. 13. Typical electrical propulsion system layout.

power station concept of electrical propulsion, the diesel generators run closer to their design point, at which they typically produce less NO_x emissions or need less fuel-consumption-increasing NO_x abatement measures. Furthermore, they always run at rated speed, as opposed to mechanical propulsion engines, which run at reduced speed in part load, producing more NO_x due to the longer NO_x formation time, as illustrated in Fig. 4.

The third advantage of electrical propulsion is the reduced maintenance load, as engines are shared between propulsion and auxiliary load and are switched off when they are not required.

Fourthly, electric propulsion can achieve reduced radiated noise due to the absence of a mechanical transmission path from the engine to the propeller. To this aim, the design of motor and power converter has to be optimised for minimal torque fluctuation. The impact of dynamic (operational) conditions on noise performance of electrical propulsion appears not to have been studied yet.

The fifth benefit of electric propulsion is its potential high availability, at least if the power and propulsion plant has been designed for this purpose.

On the contrary, electrical propulsion faces the following challenges:

- Due to the additional conversion stages in power converters and electric motors, electrical propulsion incurs increased losses. These losses lead to an increase in SFC, particularly near top speed of the ship.
- When running redundant engines to achieve high propulsion availability, which is required for sensitive DP operations, the engines run at low part load. This leads to poor fuel consumption and a lot of emissions.
- Most ships with electric propulsion use FPP, because electric motors with variable speed drives can provide maximum torque at every speed and run in reverse. Vrijdag [27] has shown that radiated noise due to cavitation increases under operational conditions when fixing propeller pitch and using speed control, which is the standard control strategy for electric motors. Therefore, cavitation potentially increases under operational conditions, particularly for electric propulsion with fixed pitch propellers and speed control, as well as for mechanical propulsion with FPP.
- Because all loads experience the electrical network voltage and frequency, voltage and frequency swings under fault conditions

can cause electrical systems to be switched off, thus reducing reliability and availability. Particularly in power systems with a high amount of variable speed drives, constant power load instability can occur. Sulligoi [40] describes this phenomenon, proposes methods to analyse the risk with two modelling strategies and discusses mitigation strategies.

As before, the control strategy should be aimed at addressing these challenges. Alternatively, when the control strategy cannot sufficiently improve any of these performance criteria, another system architecture can be selected.

3.2. Application of electric propulsion

Even though the fuel savings attributed to the power station concept are mostly offset by the increased electrical losses, electric propulsion has been very successful in the cruise industry. This is mainly attributed to the robustness of the power station concept; failure of a diesel generator has hardly any impact on the operation of the vessel [39]. Additionally, electrical propulsion allows flexibility in positioning machinery spaces, due to the absence of the shaft-line, which traditionally determines the engine room layout. Finally, the absence of the shaft-line also allows isolation of noise from the diesel engines, by installing diesel-generator sets on flexible, noise-isolating mountings.

Due to its success in the cruise ship industry, electric propulsion has also been applied in ferries, DP drilling vessels, cable layers, icebreakers, and capital naval vessels. A review of these applications and the associated developments in applied motor and converter technologies can be found in Moreno and Pigazo [38]. The choice for electric propulsion on these vessels is mainly determined by their diverse operating profiles, as these lead to a large benefit for the power station concept.

The robustness of electrical propulsion has also contributed to its success in the offshore sector, because an electrical propulsion architecture allows redundant components such as generators, thrusters, and propulsors of different types to be added easily. This feature of electric propulsion is particularly important for DP to guarantee maintaining position in fault conditions. For example, running redundant engines as spinning reserve guarantees availability of sufficient power in failure conditions.

However, running extra engines causes part load operation and therefore lower efficiency and increased NO_x emissions, as illustrated in Fig. 4. Moreover, the requirement for sufficient spinning reserve and sufficient installed power to maintain DP capability during the worst-case fault also drives installed power and thus investment cost. To overcome this, Wärtsilä offers a patented variant of the commercial standard AC architecture as depicted in Fig. 14, in which the bus bars of two generator sets are galvanically isolated from each other with a phase shift transformer. This mitigates the need for phase shift propulsion transformers (used in conventional propulsion drives) and reduces the impact of a bus bar failure to 25% of installed power instead of 50% [41,42].

The success of electrical propulsion in commercial ships and the drive to reduce running cost has prompted significant development programmes to enable electric propulsion for naval destroyers in the UK and US [43–52]. These development programmes were targeted to increase the power density with advanced technologies, consisting of new permanent magnet and high temperature superconducting motor technologies in order to fit electric propulsion in frigates and meet military requirements.

These development programmes have led to the application of electric propulsion in Royal Navy's Type 45 destroyer [53,54] and Queen Elizabeth aircraft carriers [55], and in US Navy's DDG-1000 destroyer [52]. In spite of development programmes for new motor technologies, these naval applications are still all based on the

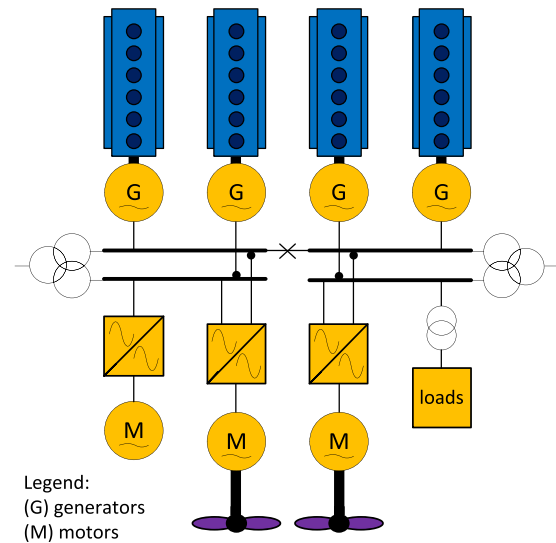


Fig. 14. Electrical propulsion layout with separated phase shifted busbars.

Advanced Induction Motor (AIM) with Pulse Width Modulation (PWM) frequency converter drives. This AIM drive is an advanced development of asynchronous motor technology. These naval applications consist of traditional fixed frequency high voltage AC generator sets with conventional control strategy, despite programmes to develop DC architectures. Therefore, the naval power and propulsion systems can also be represented by the typical propulsion system layout illustrated in Fig. 13. However, their converters can be connected to the feeding bus without transformers. The absence of these transformers increases harmonics, which are mitigated by passive and active filters [53].

3.3. Control strategies for the electrical network

The control strategy for electrical propulsion architectures consists of two parts: the control of the electrical fixed frequency network aiming to provide robust power supply to all electrical users, and the control of the propulsion aiming to drive the ship in a certain speed and direction.

3.3.1. Voltage and frequency control

The electric propulsion architectures nowadays consist of fixed frequency AC electrical networks. The frequency of the network is typically maintained by droop speed control in governors or by electric isochronous load sharing between governors. In the first case, with multiple generators in parallel, the droop in the governor controls the load sharing of active power between these generators. Similarly, the Automatic Voltage Regulator (AVR) maintains the required voltage and governs reactive load sharing between parallel-running generators. These control loops form the primary control level [56].

The main disadvantage of fixed frequency networks is that the diesel generator always runs at its rated speed. Fig. 3 shows that the specific fuel consumption of a typical engine running at reduced power and nominal speed is significantly higher than when the engine operates on the propeller curve under design conditions. A similar argument applies for CO₂ and other fuel-related emissions. However, NO_x emissions are typically lower when the engine runs on the generator line (see Fig. 4). Furthermore, the centrifugal forces in the engine, and engine wear, are higher when the engine runs at rated speed in part load.

An alternative approach is a variable frequency electrical network as proposed in Simmonds [57]. This can lead to fuel savings

of approximately 5% for a typical diesel generator set. However, electrical equipment designed for variable frequency AC networks is only limitedly available. Moreover, additional power conversion would be required to provide power to constant frequency auxiliary loads, leading to increased conversion losses. Alternatively, a DC electrical network can be selected.

3.3.2. Secondary power management control

The PMS performs secondary control, as depicted in Fig. 15. It controls the speed and voltage setpoints as to maintain voltage and frequency within the operating limits of the system during system dynamics. Moreover, during load changes the PMS provides automatic starting and stopping of generator sets and ensures online engines are not overloaded by limiting propulsion drives and other loads as necessary. Finally, the PMS can perform protection functions such as preventing blackout, switching off faulty system parts and reconfiguring the electrical network after blackout. These control actions typically are all rule-based [58] and can also be initiated by the operator. Specifically for ships with high availability requirements, such as DP vessels, the power management system is also responsible for ensuring sufficient spinning reserve is available.

The next sections cover advanced control strategies that can improve the function of the PMS to maintain voltage and frequency under fault conditions.

3.3.3. Real-time model based power management

Amgai and Abdelwahed [59] propose the *interaction balance principle* that uses sub models of the loads and power sources to calculate the optimum frequency setpoint for each power source, to achieve the globally defined target frequency. The interaction balance principle can maintain system frequencies after generator blackout within the specified range while a system with speed governors without secondary control in the presented case drops below the specified minimum. However, a performance comparison with electric isochronous load sharing governors or central secondary control has not been undertaken.

3.3.4. Power tracking

Seenumani et al. [60] propose a multi time-scale approach for power tracking with two power sources with different dynamic properties. The work demonstrates that this approach can ensure fast and efficient power tracking due to its computational effi-

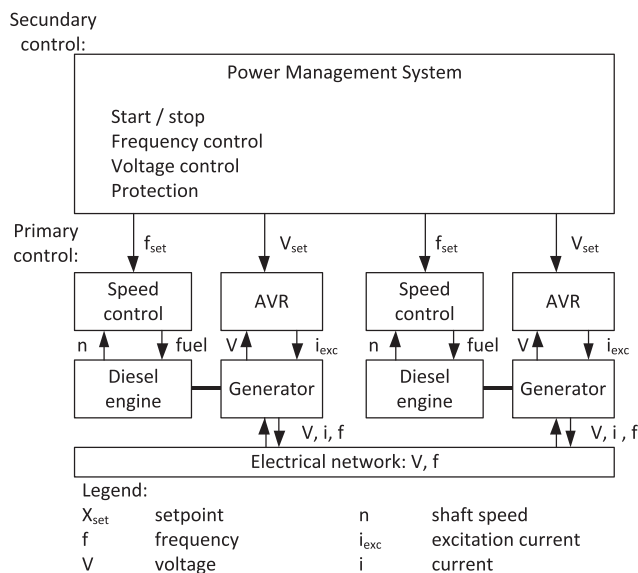


Fig. 15. Typical layered control strategy for fixed frequency AC networks.

ciency. However, the system architecture is highly simplified and constraints on engine loading appear not to have been applied, as the engine load increase is very steep in the presented results.

3.4. Control strategies for propulsion control

The second part of control for electrical propulsion architectures is propulsion control. Propulsion control has to provide the ships thrust to propel the ship at a certain speed and, in the case of steerable thrusters, in a certain direction. Most electrical propulsion systems utilise fixed pitch propellers, because the electrical drive can run at every speed in forward and reverse direction and deliver full rated torque at every speed. As such, the speed of the ship can be fully controlled without the need for a controllable pitch propeller. The control strategy for the electric propulsion motor drive, therefore, is aimed to achieve the required shaft speed. Controlling the propulsion motor torque and flux by controlling the switching signals of the PWM converter fulfils this aim. The control strategy is schematically presented in Fig. 16.

Depending on how accurate this control needs to be, torque control using *Field Orientation*, *Direct Torque Control* or *Direct Self Control* can be applied. These torque control strategies are mostly used in combination with an outer speed control loop. An extensive description of these control-methods for induction motors and references to the associated literature can be found in Trzynadlowski [61]. These modern control strategies can achieve almost instantaneous control of torque of the electric motor and, therefore, meet any requirement as defined for the drive. Furthermore, electric motors can provide full torque at every speed and can deliver above nominal torque for short time periods. Nevertheless, the diesel generator has to provide the load drawn from the electrical network. Thus, the speed of control directly influences the loading of the diesel generator and as such the diesel generator imposes restraints on the control of the electric motor.

3.4.1. Torque and power control

While most electric propulsion drives use speed control, as illustrated in Fig. 16, electric drives with torque and power control

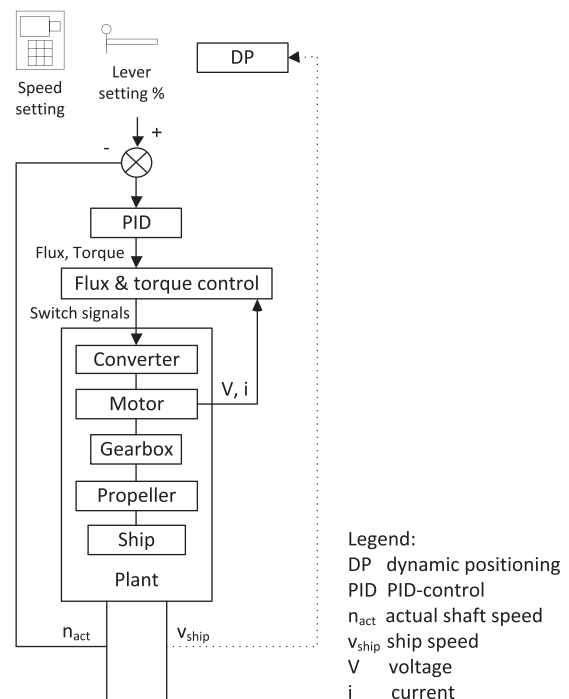


Fig. 16. Typical schematic presentation of control strategy for electric drive.

can significantly reduce thrust, torque and power fluctuations [62], as Faber [33] already concluded for mechanical propulsion. Sørensen and Smogeli [62] compare speed, torque and power control and conclude thrust losses in heavy seas are significantly reduced with both torque and power control. A combined torque and power controller demonstrates the most robust tracking performance in normal conditions. However, in extreme conditions due to heavy weather, the propeller can lift out of the water or endure ventilation. In these conditions, torque and power control can lead to propeller over-speed. Smogeli et al. [63] propose two control strategies to prevent propeller over-speed: one that bounds the propeller speed with a PID control action and one that detects ventilation and subsequently reduces torque or power to reduce shaft speed to a value at which thrust loss does not occur any longer. While the first strategy prevents propeller over-speed, the second strategy achieves minimal thrust loss and highest propulsive efficiency. Similar to these strategies, Zhao et al. [64] propose to reduce the shaft speed setting with a *speed modulation* control strategy when ventilation occurs, again, to reduce thrust loss.

4. Hybrid propulsion

When the auxiliary load is only a fraction of the required propulsive power, the losses associated with the electrical conversion lead to increased fuel consumption for electric propulsion systems [65]. The extra electrical equipment also leads to increased weight, size and cost [66]. Therefore, ships that frequently operate at low speed can benefit from a hybrid propulsion system [67,68]. In hybrid propulsion, a direct mechanical drive (1) provides propulsion for high speeds with high efficiency. Additionally, an electric motor (2), which is coupled to the same shaft through a gearbox (3) or directly to the shaft driving the propeller, provides propulsion for low speeds, thus avoiding running the main engine inefficiently in part load. This motor could also be used as a generator for electrical loads on the ships services electrical network (4). A typical layout for such a hybrid propulsion system is presented in Fig. 17.

When the mechanical drive engine is running, this system allows generating capacity either from the electric generator or from the generating sets. Typically, rule-based control or the operator determines the generating capacity.

4.1. Benefits and challenges of hybrid propulsion

Because hybrid propulsion is a combination of electrical and mechanical propulsion, it can benefit from the advantages of both, as discussed in Sections 2 and 3. However, in order to achieve these benefits, a proper design (of the hybrid propulsion) is required and often a trade-off between these requirements has to be made. The control strategy allows an optimal trade-off and can use the extra degree of control by transferring electrical power from the mechanical drive to the electrical network and vice versa. The main challenge for the hybrid propulsion design is to balance the trade-off between all requirements and design a control strategy to achieve this balance.

4.2. Application of hybrid propulsion

Typical applications of hybrid power and propulsion systems are naval frigates and destroyers [67,68], towing vessels [69] and offshore vessels [8,9]. Castles and Bendre [67] describe the economic benefits of a hybrid propulsion system for US Navy DDG-51 class assuming rule-based control. The US Navy uses gas turbines as its prime movers, also for its ship services' generators. The part load specific fuel consumption of gas turbines is very poor,

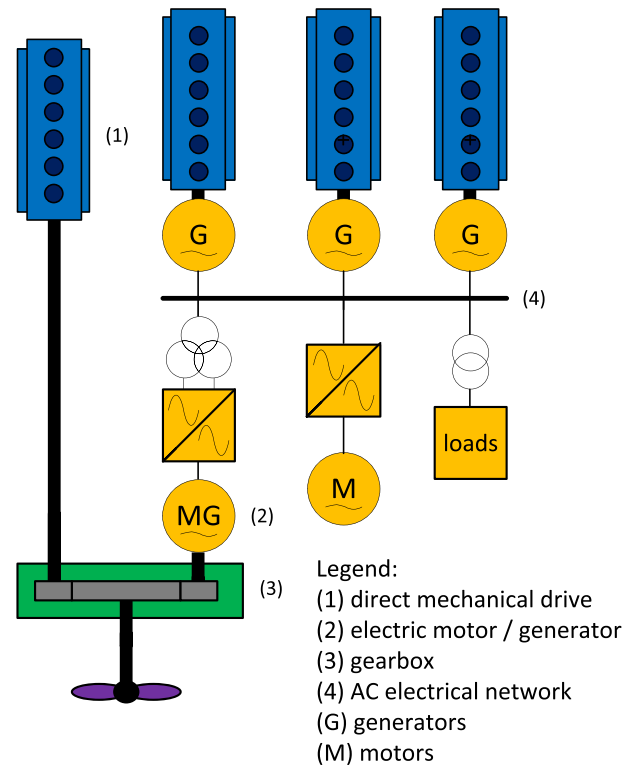


Fig. 17. Typical hybrid propulsion system.

much worse than that of diesel engines. With gas turbines, hybrid propulsion thus can lead to significant fuel savings. Sulligoi et al. [68] discuss the Italian Navy *FREMM* frigate configuration with diesel generators and a sprint gas turbine main engine. However, they do not discuss the economic benefits. Wijsmuller and Hasselaar [69] compare the economic benefits of a number of hybrid-propulsion architectures for an emergency towing vessel. With the operational profile of this vessel, the engine power is 20% or less at 90% of its operational time. The most economical configuration for the given operational profile was hybrid propulsion with a large and small engine on each shaft, supporting medium patrol speeds (45% of the time) efficiently, and using electric propulsion for low speed patrol and loitering speeds (45% of the time). Finally, Barcellos [8] presents case studies in applying hybrid propulsion to offshore vessels. These studies show that the increased transit distance in combination with stringent availability requirements for DP operations suit hybrid propulsion very well. The mechanical propulsion plant can be optimised for efficient transit and the electrical plant for DP operation with high availability. Thus, fuel savings of more than 10% were achieved. The results from these studies support the assumption that hybrid propulsion is typically economical when the operational profile has distinct operating modes with a significant amount of time at low power. Similarly, de Waard [70] found that hybrid propulsion provides economic benefits if the vessel sails a significant amount of time below 15% propulsive power, equivalent to 40% of its top speed.

4.3. Control strategies for hybrid propulsion

The current control strategies applied in practice and covered in literature for hybrid propulsion are based on two operating modes: mechanical drive and electrical drive. First, the control strategies discussed in Section 3 apply to electric drive mode. Second, the control strategies as discussed in Section 2 apply to mechanical drive mode. In this mode, the electric machine can be switched

off, used as an electric assist motor or used as a shaft generator. However, very few applications use the electric motor in parallel with the mechanical drive, as will be discussed next.

4.3.1. Shaft generator control

The electric motor can run as a shaft generator if the prime mover has sufficient load margin. In the Italian Navy FREMM frigate configuration the engine driving the shaft is a gas turbine engine with a free power turbine. Due to the free power turbine maximum engine power is available at any shaft speed. Therefore, sufficient load margin is always available, unless the ship is sailing at top speed in off-design conditions. Thus, implementing the electric motor as a shaft generator is feasible for this configuration [68]. The control strategy applied to the converter of the shaft generator is speed and voltage droop control for the power generation plant side of the power converter. Moreover, the electric machine side of the converter uses field oriented control, which is adjusted for the current supplied by the power system side of the converter to maintain the DC voltage. These strategies combined prove to be successful in running a shaft generator and diesel generator in parallel, according to the work performed in Sulligoi et al. [68]. However, due to using speed and voltage droop control, the load dynamics are shared equally between the shaft generator and the diesel generator. This might not make optimum use of the gas turbine power that is available, as the gasturbine can handle load dynamics more easily than the diesel generator. Alternatively, running the diesel generator in speed droop control and the shaft generator in isochronous control would force the gasturbine to handle all dynamics. However, further research would be required to determine whether this could lead to a stable control strategy.

4.3.2. Electric motor assist

When the electric drive is designed to run in parallel with the mechanical drive, it can be used to increase the top speed of the ship and reduce the engine thermal loading and thus NO_x emissions. Topaloglou et al. [71] propose a control strategy that uses the electric motor torque to reduce the main engine's air excess ratio λ , which indicates the amount of air available in the engine cylinder during combustion, and therefore is a measure of engine thermal loading. The proposed control strategy increases torque of the electric drive to maintain the reference λ value, which is a result of a static map as a function of engine torque, speed and charge pressure. During an acceleration manoeuvre simulated on the testbed of the National University of Athens, the proposed strategy achieves a 16% reduction in NO_x emissions and a 0.25 increase in minimum air excess ratio λ from 1.85 to 2.15, thus significantly reducing engine thermal loading during acceleration manoeuvres. Therefore, the proposed strategy clearly demonstrates the potential of performance improvement when the electric drive is used in parallel with the main diesel engine.

5. Electrical propulsion with hybrid power supply

In electrical propulsion with hybrid power supply, a combination of two or more types of power source can provide electrical power. We propose to classify power sources into:

- Combustion power supply, from diesel engines (1), gas turbines or steam turbines;
- Electrochemical power supply from fuel cells; or
- Stored power supply from energy storage systems (2) such as batteries, flywheels or super capacitors.

While extensive literature is available on the development of fuel cells, commercial application of electrochemical power supply

in the maritime environment is limited. Van Biert et al. [72] provide a review of fuel cell systems for maritime applications, which includes an overview of maritime fuel cell research applications. Application of series production fuel cells on board has been limited to air independent propulsion on submarines, as the storage of the hydrogen fuel limits the amount of energy that can be produced without refuelling [73,74]. Research now is focussed on more compact storage of hydrogen [73], fuel cells with or without reformers that can use other fuels such as methanol, LNG or even diesel oil [75], and fuel cells combined with diesel engines or gas-turbines to achieve high efficiencies while using more energy dense fuels [72].

The development of stored power supply for automotive and power system application is an extensive research area. However, purely stored power supply on ships is limited to ferry *MV Ampère*, due to its limited range. The available energy storage technologies are categorised in Roskilly et al. [76] and covered extensively in its references. Research into energy storage technology on board ships is significantly more limited and primarily focussed on the use of battery technologies [77,17,78,79], although Lan et al. [77] address sizing of a hybrid combination of combustion, photovoltaic (PV) and stored power supply. Specifically for handling pulsed loads on naval vessels, hybrid energy storage technology is required to supply up to 10 GW during microseconds bursts to high energy weapons. This hybrid energy storage combines high power density of ultra capacitors with high energy density of batteries [80]. In the remainder of this paper, the main type of energy storage to be considered is the battery.

The idea to use battery energy storage for propulsion originates from the automotive industry, which increasingly uses batteries to store braking energy instead of dissipating it, to run the engine in a more efficient operating point, and to enable switching off the main engine, particularly when operating at no load or part load. A typical architecture of an electrical propulsion plant with hybrid power supply is shown in Fig. 18. In this case, energy storage (2) is connected to the main distribution bus. However, energy storage can be connected at various locations of the electrical system:

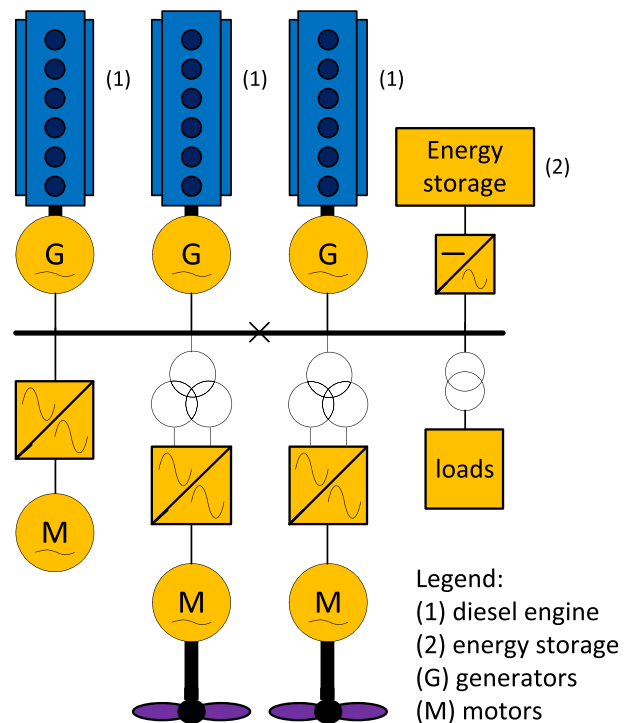


Fig. 18. Typical electrical propulsion system with hybrid power supply.

- At the main high voltage bus bar through an AC/DC converter;
- At the LV bus bar through an AC/DC converter;
- Directly or through a DC/DC converter to the DC link of the propulsion converter.

5.1. Benefits and challenges of electrical propulsion with hybrid power supply

The benefits of applying stored and hybrid power supply in ship power and propulsion plants can be diverse:

- The energy storage can provide the required electrical power and enable switching off one or more engines when they would be running inefficiently at part load. The energy storage can then be recharged when the engine is running in an operating point with lower SFC and CO₂ and NO_x emissions. This can save fuel, reduce emissions, reduce noise, increase comfort and enable temporarily sailing without emissions, noise and vibrations from the engines [17].
- The battery can enable load levelling, by handling the power fluctuation. This results in constant loading of the engines, maintaining a more efficient operating point. Dedes et al. [79] propose a hybrid propulsion configuration with hybrid power supply for dry bulk carriers and indicate this configuration could achieve significant savings in fuel consumption, CO₂ and NO_x emissions.
- The battery can enable peak shaving; the battery delivers power during periods where high power is required and recharges when less power is required. This strategy can run engines more efficiently and reduce installed power [79].
- When the battery is recharged from the grid alongside, this can reduce fuel consumption and local emissions. However, the cost and emissions of power generation in the grid then has to be taken into account, although this power might be generated from renewable energy sources [10,12].
- The battery can be used to store regenerated energy when braking on electric motors. In current electric propulsion plants, this energy is dissipated in braking resistors. However, the fuel savings due to storing braking energy from propulsion are limited because ships do not often have to stop quickly. On the other hand, significant energy can be regenerated in ships with heavy crane installations [78] and in offshore and drilling vessels with heave compensation.
- The battery can provide back-up power during a failure of combustion power supplies (diesel generators). This can omit the need for running extra diesel engines as spinning reserve and can potentially reduce the installed power on vessels with a requirement for a high availability of propulsion, for example DP vessels [17].

The battery in a hybrid power supply runs in parallel with generators. This leads to the following challenges:

- The control strategy needs to maximise the reduction in fuel consumption and emissions, by charging and discharging the battery at the right time.
- Load fluctuation on diesel engines increases fuel cost, emissions and maintenance load. Thus the control strategy should ideally share dynamic load between the battery and the diesel engine in such a way that the fuel cost, emissions and maintenance load of all power suppliers are minimised.
- The increase in purchase cost due to the installation of batteries needs to be minimised or offset by reduced installed power from diesel engines.

5.2. Application of electrical propulsion with hybrid power supply

Batteries have only recently been applied in maritime applications, but their popularity is growing very quickly. For tugs and ferries, for example, the potential reduction of fuel consumption and emissions has led to investigation and application of electrical propulsion with hybrid power supply [10,12]. Batteries have also been used increasingly in offshore. However, most offshore applications have been equipped with a DC electrical network, to be covered in Section 7.

Volker [10] investigates the economic benefits of an electric propulsion system with hybrid power supply for towing vessels and ferries. Both case studies consider batteries for energy storage with rule-based control. The calculated fuel savings of the hybrid propulsion plant are marginal when the battery is not recharged from the shore grid. The results of studies like these, however, strongly depend on the operational profile. Moreover, no sensitivity studies have been performed.

Alternatively, the ferry *MV Hallaig* with electrical propulsion and hybrid power supply has demonstrated the potential of this architecture when using advanced control strategies. This ferry, delivered by IMTECH in 2014, is illustrated in Fig. 19. Fuel savings of 35% were demonstrated during trials, caused by two effects. First the batteries were charged overnight, leading to 24% fuel savings. For this 24% fuel saving, electrical power from the grid was used, which has to be accounted for. However, using renewable energy for this power can significantly limit the environmental impact. Moreover, local emissions in the operating environment of the ferry are reduced with this concept. The second part, 11% fuel savings, was attributed to optimising the use of the engine and the battery over the operating cycle of the ferry with the energy management system [12,13,81].

5.3. Control strategies for electrical propulsion with hybrid power supply

Microgrids in the terrestrial grid often combine fossil-fuel power sources with renewable energy sources and energy storage and can thus be classified as a hybrid power supply. Therefore, literature on microgrid control strategies could provide useful insight into control of hybrid power supplies on ships. The control strategy for hybrid power supply consists of three levels: primary control, secondary control and tertiary control [82,83]. Unamuno and Barrena [83] classify primary control strategies into grid following and grid forming strategies, which are applicable to ships connected to the shore connection and at sea respectively; secondary strategies



Fig. 19. Ferry with electrical propulsion and hybrid power supply.

into centralised and non-centralised control; and tertiary strategies into centralised and distributed control strategies. Subsequently, they review and classify the strategies proposed in literature.

First, primary control has to achieve voltage and frequency stability. For completeness, Han et al. [84] review and classify communication-based control strategies and droop-characteristic-based control strategies for inverter fed AC microgrids. However, generators on ships are connected to the grid directly, as opposed to most microgrid distributed generation (DG), which is often connected through frequency inverters [84]. Therefore, the primary control strategy is droop control, as discussed in detail in Olivares et al. [85] and Zhang et al. [86], and also proposed for shaft generator control on the grid side in Sulligoi et al. [68] (Section 4.3.1). Moreover, this droop control strategy also achieves a scalable hierarchical control strategy for a multizone grid, as discussed extensively in Guerrero et al. [82]. Thus, the zonal distribution system can be very robust for failures in grid sections, which is of particular interest for naval vessels, offshore ships and future autonomous vessels that require a high degree of availability and reliability [87,88]. To conclude, Sudhoff et al. [89] describe a reduced scale naval DC microgrid that demonstrates such a zonal distribution system using droop control.

Secondly, secondary control strategies aim to correct the deviations in voltage and frequency, and balance demand and supply [82] (see also Section 3.3.2). Unamuno and Barrena [83] classify secondary control for microgrids in centralised and non-centralised control. Ships power systems typically use centralised secondary control due to the limited size of the grid, although distributed control strategies might be considered for ships with very high continuity of power demands, such as naval ships, and might be an interesting enabler for future autonomous vessels [88,90,91].

When microgrids are connected to the grid, their tertiary control manages the active and reactive power flow to and from the main grid by centrally changing the global voltage and frequency settings of the microgrid as described by [82]. Unamuno and Barrena [83] also review tertiary control strategies that use distributed management. These tertiary strategies only apply to the ships grid when connected to the shore connection and running at least one of its own power sources in parallel, which currently is not common practice. Alternatively, Shi et al. [92] propose a distributed Energy Management System (EMS) that solves the optimal power flow problem of the microgrid both in island and grid-connected operation. They consider a cost function for the use of the battery that allocates cost to fast charging, switching between charging and discharging, and deep discharging. This strategy has a strong resemblance with energy management strategies used in automotive applications and can be applied to ship's hybrid power supplies.

The remainder of this section will discuss options for tertiary energy management of hybrid power supplies; to determine the power split between the different power sources. Sciarretta et al. [11] discusses a comparison between various EMS strategies using a control benchmark. The strategies are classified as heuristic control strategies that are rule based and Equivalent Consumption Minimisation Strategies (ECMS) that solve an optimal control problem to minimise fuel consumption [20]. These strategies and the equivalent maritime strategies will be discussed next. Subsequently, control strategies that consider the future operating profile and uncertainties in their control problem [93,94] and that are aimed at levelling the generator load based on the historic load profile will be covered [78].

5.3.1. Heuristic control strategies

In heuristic control strategies, logical rules determine the operating mode of the plant and the setting for the battery charge and

discharge system. When the battery is applied to serve distinct operating modes, heuristic control strategies can achieve the aim of the design. For example, when a ship needs to be able to run silently or without emissions during certain periods, the engines can be switched off in this operating mode. Also fuel savings can be achieved with rule-based control, particularly when the operating profile consists of discrete, distinct operating modes.

An example of such a rule-based control strategy is described in Sciberras and Norman [95]. This control strategy utilises the battery at low speeds for propulsion while shutting down the engine, and at high speed to electrically assist the engine. Sciberras and Norman [95] demonstrate that the amount of fuel saved by such a strategy depends on the battery capacity and thus system weight and cost. However, a comparison with a baseline without batteries lacks.

Another heuristic control approach is the map-based approach. In this approach multidimensional maps, whose entries are system parameters, determine the selection of the operating mode and the system settings. In the automotive industry this approach can achieve good fuel efficiency, although the Equivalent Consumption Minimisation Strategy (ECMS) outperforms heuristic control [11]. Map based heuristic control has not been covered in maritime applications or research yet to the best of our knowledge.

5.3.2. Equivalent consumption minimisation strategy

In the Equivalent Consumption Minimisation Strategy (ECMS), the optimum power management setpoints are calculated with an optimal control problem formulation that minimises the fuel consumption of the engine and the equivalent fuel consumption of the battery, which accounts for the fact that the battery needs to be recharged. In a comparison of various control strategies against a control benchmark of a hybrid electrical vehicle, various variants of the ECMS consumed the smallest amount of fuel when simulated over an unknown operating profile [11]. A schematic presentation of such a control strategy for hybrid power supply using ECMS is presented in Fig. 20. The energy management system of the hybrid ferry discussed in Section 5.2 uses an ECMS optimisation strategy. In this strategy, cost functions are defined for the fuel use of all power suppliers, including the battery. Load is shared between power supplies to minimise cost. Fuel savings of 10% due to the energy management system were demonstrated during operational trials [12,81].

5.3.3. Power management through operating load estimation

Similarly, Vu et al. [93] cover a power management scheme that determines the optimal power split based on a known future operating profile. This strategy uses the nonlinear optimisation approach to find the minimum of a cost function that accounts for fuel consumption and battery life. Furthermore, the strategy can also control discrete events such as the starting and stopping of multiple generators, as opposed to automotive strategies, which consider only a single engine. If the future operating profile is not known in advance, the strategy uses a novel load prediction scheme, which anticipates future load demand based on historical load demand data.

In a case study of an Electric Tug, Vu et al. [93] show that the proposed strategy can achieve a 9% performance improvement for the combined cost function compared to a rule-based controller as described in Sciberras and Norman [95]. This improvement is mainly due to the fact that the optimal power management scheme ensures the battery is at its minimum charge at the end of the operating cycle while the rule based controller aims to maintain maximum battery charge; the battery delivers 7% of the required energy for the given operating profile, and the power flow optimisation accounts for 2% fuel consumption reduction. Finally, Haseltalab et al. [94] propose an Energy Management strategy that

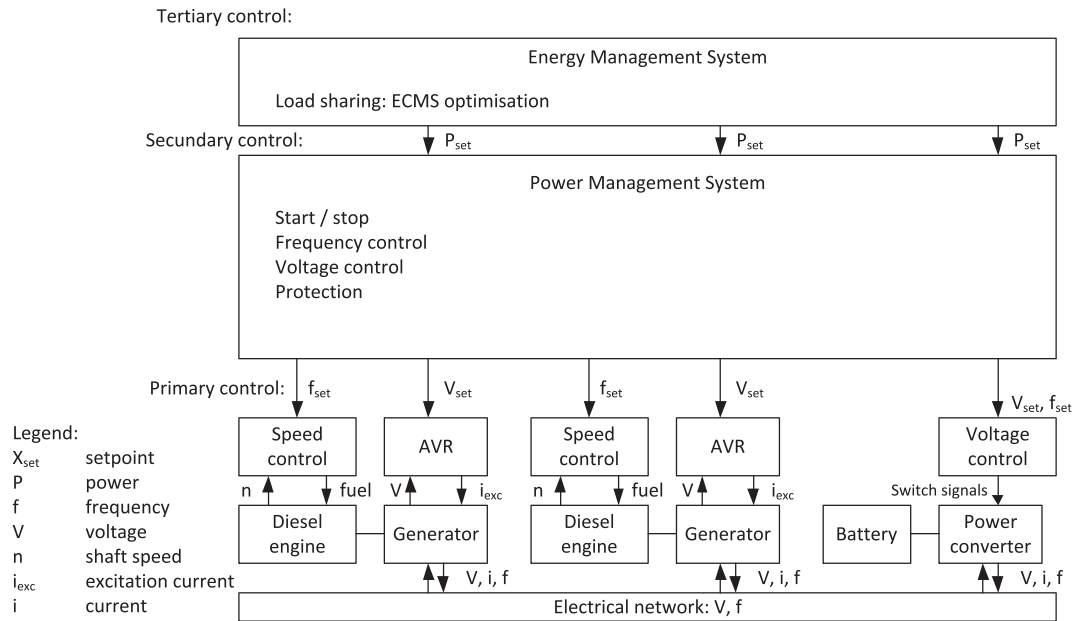


Fig. 20. Control strategy for hybrid power supply with ECMS.

uses Model Predictive Control to account for future power demand in the presence of uncertainty and environmental disturbances. They demonstrate the feasibility of this approach with a simulation study.

5.3.4. Load levelling

When the engine operates close to the optimal working point from a fuel consumption perspective, load fluctuation due to fluctuating propulsion load (in high sea state) or other load disturbances, can cause increased fuel consumption. Then, providing (a percentage of) the fluctuating load from a battery can reduce the fuel consumption increase. Furthermore, dynamic engine loading can be reduced, potentially reducing engine wear. This strategy can particularly deliver fuel savings for transient loads like cranes or dredging pumps. For example, the fuel consumed during crane operation on a dry bulk vessel of 50,000 dwt can be reduced about 30% with the novel hybrid control strategy proposed in Ovrum and Bergh [78]. This energy management strategy aims to run the diesel generator at the average required power demand over the operating profile, looking at the historical power demand only, and uses battery charging and discharging to supply the load transients. Moreover, the maximum rate of charging and discharging can be limited to reduce ageing of the battery.

6. Hybrid propulsion with hybrid power supply

Hybrid propulsion with hybrid power supply utilises the maximum efficiency of direct mechanical drive (1) and the flexibility of a combination of combustion power from prime mover(s) (2) and stored power from energy storage (3) for electrical supply. At low propulsive power an electric drive (4) is available to propel the ship and switch off the main engine (1). The machine providing electric drive can also be used as a generator. A typical architecture is illustrated in Fig. 21.

Below, the application of this architecture will be covered and subsequently the control strategies for hybrid propulsion with hybrid power supply. An overview of control strategies that can be applied for hybrid propulsion has been covered in Section 4 and an overview of control strategies for systems with hybrid power supply in Section 5.

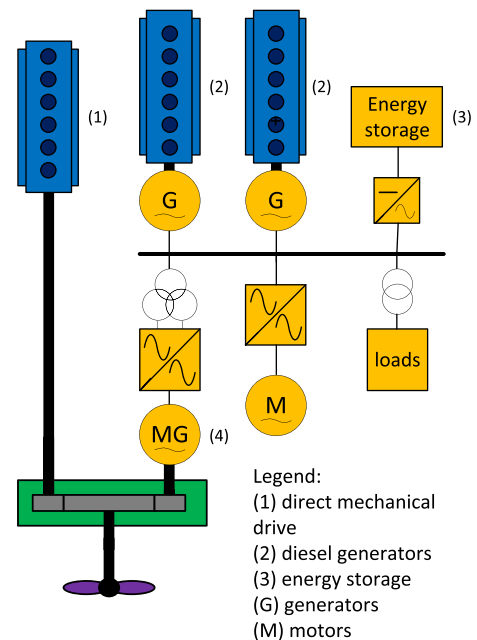


Fig. 21. Typical hybrid propulsion system with hybrid power supply.

6.1. Application of hybrid propulsion with hybrid power supply

Hybrid propulsion with hybrid power supply has first been researched extensively in harbour tugs. Following this research, Damen delivered the first tug with hybrid propulsion and hybrid power supply in 2014. An overview drawing of the vessel is shown in Fig. 22.

Moreover, hybrid propulsion with hybrid power supply has been applied to the yacht *Savannah*, which Feadship launched in 2015 [32]. To the best knowledge of the authors tugs and yachts are currently the only applications in which the combination of hybrid propulsion and hybrid power supplies has been studied or implemented.

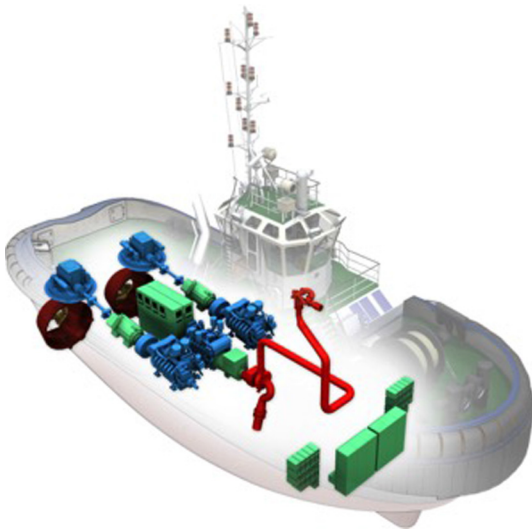


Fig. 22. Overview drawing of hybrid harbour tug.

6.2. Control strategy for hybrid propulsion with hybrid power supply

The control strategies that have been investigated for hybrid propulsion with hybrid power supply will be covered in this section.

6.2.1. Heuristic control strategy

Research at Delft University of Technology, suggests that hybrid propulsion with hybrid power supply can deliver significant savings in local emissions, partly by using energy from the batteries that are recharged with a shore connection [96–98]. These savings can be achieved with a heuristic rule based approach. In this approach the control mode of the plant is determined by the operating mode of the vessel (towing, high speed transit, low speed transit or standby) and the battery state of charge.

This approach can achieve positive results, because the operating modes of the plant lead to very distinct loading of the system. For example, in low speed transit or standby the main engine loading is very low and, therefore, switching off the engine stops the engine operating inefficiently. However, the amount of fuel and emission savings that can be achieved with a heuristic control strategy strongly depends on the operating profile of the ship and on the sizing of the components.

Furthermore, the hybrid propulsion configuration allows designs in which the main engines cannot deliver full bollard pull on their own. However, a design that for delivery of full bollard pull depends on an electric motor or batteries potentially introduces reliability and safety risks. Thus, in current designs the main engine is sized to deliver full bollard pull without additional power from the electric motor.

6.2.2. Equivalent consumption minimisation strategy

In Grimmelijs et al. [97] the models required for an ECMS control strategy for hybrid propulsion with a battery as a single electrical power supply are introduced and the application on a tug as a test case is presented. The application does not include a comparison with a rule-based strategy so the benefits of the approach have not yet been established for the case study. Furthermore, practical applications tend to use diesel generators as well, further complicating the optimisation strategy. However, the models used in Grimmelijs et al. [97] only need minor additions to include a diesel generator power source.

7. Electrical propulsion with DC hybrid power supply

One of the major drawbacks of electrical propulsion is that the fuel consumption of the engine in part load is higher for an engine running at fixed speed than for an engine running at variable speed (such as a direct drive engine). This was illustrated by the fuel consumption curves in Fig. 3. This drawback of electrical propulsion has led to the concept of variable frequency electrical networks as discussed in Section 3. Application of variable frequency networks has been very limited, mostly because other consumers require fixed frequency power supply. However, DC distribution systems can also enable variable engine speed.

Historically, DC systems have been applied in specific applications such as submarines. However, fault protection and power system stability issues have limited their application. The continued development of power electronics [51] and intelligent schemes to protect against faults [15] and ensure power system stability [16,99] have enabled more widespread application of DC systems. The most important reasons for applying DC systems are increased fuel efficiency when running generators in part load and reduced power conversion losses [17]. A typical architecture of electrical propulsion with DC hybrid power supply is presented in Fig. 23.

7.1. Benefits of hybrid DC power supply

The benefits of applying hybrid DC power supply to ships with electric propulsion are as follows:

- The DC architecture allows to run the diesel engine at variable speed, potentially leading to a reduction in fuel consumption, emissions, noise and engine mechanical and thermal loading.
- DC architectures are resilient to faults, because power electronics allow instantaneous control of electrical variables and electrical faults do not spread across the electrical network and disturb network voltage and frequency.
- The amount and size of switchgear potentially reduces when the power electronics in the system perform fault protection [15].

Although DC architectures can provide significant benefits, the following challenges need to be resolved:

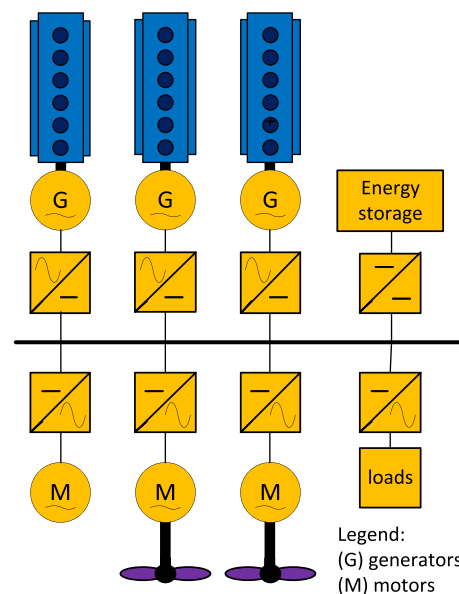


Fig. 23. Electrical propulsion with DC hybrid power supply.

- All power sources and loads need to be connected to the DC network through power electronic converters. If a large amount of fixed frequency AC loads need to be fed, this can lead to a significant cost increase. However, if a significant amount of the total load is already fed through variable speed drives, DC architectures can lead to cost reduction [100].
- In order to enable DC architectures, fault protection needs to be resolved [15].
- A coordinated control strategy is required to resolve stability issues and achieve optimal performance for the criteria listed in Section 1 [16,99].

7.2. Application of electrical propulsion with hybrid DC power supply

Traditionally, DC power supply systems have been applied in submarines in combination with large battery packs to enable air independent propulsion. More recently, the US Navy has also applied a DC distribution system to its DDG-1000 destroyers [52,101,102]. Similarly, the Royal Navy has considered DC power systems for its frigates in an extensive development programme, but has not implemented them yet [43–51,15]. Both these navies applied or considered DC power systems for their resilience and to enable pulsed power loads. The designs contained a great amount of power electronic conversion equipment that was used to decouple voltage and frequency of different parts of the system, thereby achieving increased resilience. A key feature of these naval DC systems is their distributed nature.

DC electrical systems have been launched extensively in recent years in ferries and offshore vessels. Alewijnse delivered the DC power system of Offshore Supply Vessel MV Jaguar in 2012, Siemens delivered its first DC system with hybrid power supply on the Platform Supply Vessel MV Edda Ferd in 2013 and, finally, ABB delivered its first hybrid DC grid in 2013 on MV Dina Star. Other applications that utilise DC hybrid power supply systems are drilling ships, research vessels and wind farm support vessels. DC was also applied on the world's first large fully electrical vessel, a ferry in Norway; Siemens delivered the MF Ampere in 2015 with a DC grid only powered by batteries.

An attractive element that has led to the application of DC grids in offshore vessels is that their major electrical consumers use variable speed drives, which have a basic DC-architecture due to its DC-link. Examples of electrical consumers that can be fed from a shared DC-link are heavy-lifting cranes, variable speed propulsion and thruster drives, heavy pumps and compressors. Another feature of these DC grids in offshore vessels and ferries is their centralised design. The system comprises one or two DC switchboards. Further distribution of electrical power typically is AC from power converters. This ensures the stability and fault protection issues only have to be solved for a small local system, and requires only a limited amount of equipment that can switch DC fault currents. However, the continued development of DC systems and intelligent fault protection that reduces the requirement for switchgear is likely to lead to more distributed DC systems in the near future [15].

Finally, DC hybrid power supply architectures appear very promising for luxury yachts, mainly to increase comfort, without losing performance. For these yachts the DC architecture allows easy integration of batteries and silent variable-speed electric drives [14,32].

7.3. Control strategy for electrical propulsion with DC power supply

This section covers the objectives of the control strategy for shipboard DC power systems and research into shipboard DC power system control.

7.3.1. Prime mover frequency control

In DC power systems, the frequency of each generator can be selected independently of other generators as the AC voltage is rectified. As such, the speed-governing control loop is not used to achieve load sharing between generators in AC systems. This allows the engine speed to be optimised for any given criteria, such as minimised fuel consumption, optimal engine loading, minimised emission and minimised noise frequency.

Zahedi et al. [17] propose a control strategy that governs engine speed to achieve minimal fuel consumption for the given load. In a simulation of an offshore support vessel over seven operating modes, the DC system with variable engine speed resulted in 8% fuel savings compared to the conventional system discussed in Section 3.

7.3.2. Load sharing

Load sharing in AC systems is achieved by frequency droop control, while the equivalent strategy for DC systems is voltage droop control [18]. Therefore, by setting different values for voltage droop for different power sources in a DC system the power ripple can be unevenly split over the power sources. Thus, in a DC system with hybrid power supply, the share of dynamics taken up by the different types of power supply can be controlled.

7.3.3. Optimum load levelling strategy

Zahedi et al. [17] propose an online optimisation strategy which utilises the battery first to run the generators at the optimum load from a fuel consumption point of view by applying a charge-discharge (CD) strategy and secondly to supply an optimum fraction of the power ripple. This CD strategy moves the operating point from an inefficient working point on k engines (k being the number of engines running to supply the required power) to a more efficient working point on k or $k - 1$ engines at lower power, while discharging the battery, and, then, to another more efficient working point on k or $k + 1$ engines at higher power, while charging the battery. This strategy thus does not aim to deplete the battery over the operating trajectory to recharge the battery from the grid.

This strategy requires determining the average power and power ripple. The average power and power ripple over a certain time interval or during an operating mode depend on future data as well. For online optimisation, these parameters are obtained filtering instantaneous values with experimentally derived time constants. In simulations, which use statistical values for a number of operating modes, the strategy results in 7% fuel savings. The results, however, strongly depend on the selection of time constants, which in practice might not be constant.

7.3.4. Model predictive control for multiple criteria

Park et al. [103] propose real-time MPC to adjust the secondary control parameters, in the study case primary generator voltage droop, secondary generator power setpoint and propulsion motor power setpoint, to optimise for multiple performance attributes while maintaining power system component constraints. The primary control loops that the secondary control influences are voltage control for the primary power source and power control for the secondary power source and propulsion motor. The work consists of numerical simulations, real-time simulations and experiments on a testbed and demonstrates that real-time MPC is feasible and can be used for a control strategy that trades off conflicting performance requirements, both for known and unknown future operating conditions.

8. Discussion and summary

This paper has classified and reviewed the major current and future power and propulsion system architectures and their asso-

ciated control strategies. This section provides an overview and discussion of the various power and propulsion architectures, their benefits and trends for future applications, as well as a summary and discussion of available control strategies and their applicability to the various power and propulsion architectures.

8.1. Power and propulsion system architectures

Table 1 summarises the benefits and drawbacks of the power and propulsion technologies covered in this paper. Table 2 presents the applications of these power and propulsion architectures and illustrates the trends by listing potential future applications for these architectures.

In the '90s, the development of power electronics led to extensive application of electrical propulsion in order to overcome the poor part load efficiency and robustness of mechanical propulsion. This electric propulsion was first introduced in cruise ships. Capital naval ships, offshore vessels and other incidental applications followed promptly, as the hotel load for these ship types is a significant part of the total load.

Later, hybrid propulsion was introduced for vessels both operating a large proportion of time at design speed, and operating significant periods at low power, below 40% of their top speed, in order to maintain the very good efficiency at design speed. For example, warships and patrol vessels have increasingly utilised hybrid propulsion, just as tugs and offshore vessels.

More recently, the development of high power batteries in the automotive industry has enabled their use in shipping. At the expense of increased purchase and replacement cost, batteries can provide load levelling, efficient back-up power and a zero-noise-and-emission propulsion mode. Batteries have thus been increasingly applied in tugs, yachts, offshore vessels and ferries, due to the reducing cost of batteries, even though system complexity increases. Moreover, the opportunity to store regenerated energy is likely to lead to hybrid power supplies in drilling vessels and crane vessels in the near future. Furthermore, fuel consumption, emissions and installed power could be reduced for cargo ships as well, if batteries are used to level propulsion load fluctuation from heavy seas.

The use of purely stored power supply from batteries is limited to vessels that require a very short range, such as ferries like *MV Ampère*. Electrochemical power supply from fuel cells can be used for submarines that require a longer, but still limited range, with hydrogen stored in metal hydride cylinders.

Furthermore, the increase in the utilisation of power electronics in AC systems for main propulsion, thrusters, variable speed pumps, compressors and other drives has enabled the introduction of DC power systems. Initially, these DC power systems consisted of a number of drives with a shared DC bus. Subsequently, all loads were provided through power electronic converters. In such a configuration, a DC grid enables diesel generators to run at variable frequency, which reduces fuel consumption and engine maintenance.

Table 1
Benefits and drawbacks of propulsion and power supply (PS) technologies.

Technology	Benefit	Disadvantage	References
Mechanical propulsion	Low loss at design speed	Poor part load efficiency and emissions	Figs. 3 and 4
	Low CO ₂ and NO _x emissions at design speed	High NO _x at reduced speed	Ko et al. [4] and Linden [31]
	Low conversion losses	Low redundancy Mechanical transmission path of noise Engine loading	Baldi et al. [29] Vrijdag et al. [104] Van Spronsen and Toussain [28] and Guillemette and Bussi�eres [30]
Electrical propulsion	Robustness Matching load with generators High availability	Constant generator speed Losses at design speed Risk of constant power load instability	Vie [39] and Moreno and Pigazo [38] Vanderpump et al. [53] Sulligoi et al. [40]
	Reduced NO _x emission at low speed Potentially low noise		Fig. 4
Hybrid propulsion	Low loss at design speed Robustness Matching load & engines at low speed Potentially low noise on electric drive	Constant generator speed System complexity	Wijsmuller and Hasselaar [69] McCoy [65] and Gemmell et al. [66] Castles and Bendre [67] Sulligoi et al. [68] and de Waard [70]
Electro-chemical PS	Air independent No harmful emissions High efficiency and low noise	Limited range Safety Complex with reforming	Sattler [73] and Psoma and Sattler [74] Van Biert et al. [72] Leites et al. [75]
Stored PS	Air independent No harmful emissions and noise	Very limited range Safety	<i>MV Ampere</i>
Hybrid power supply	Load levelling	Constant generator speed	Dedes et al. [79] and Volker [10]
	Zero noise and emission mode Storing regenerated energy Efficient back-up power Enabling pulsed power Reduced fuel consumption & emissions	System Complexity Safety due to battery Battery cost	van Loon and van Zon [32] Ovrum and Bergh [78] Zahedi et al. [17] Lashway et al. [80] Breijs and Amam [12], Rampen and Breijs [13], and Vu et al. [93] Fig. 4 and Topaloglou et al. [71]
	No NO _x increase during acceleration		
DC power supply	Variable engine speed and load Optimal engine loading	System complexity Cost & losses from power electronics NO _x increase due to variable speed	Zahedi et al. [17] van Loon and van Zon [32]
	Reduced engine noise and vibrations Reduced fuel consumption and CO ₂ Enabling pulsed power		Butcher et al. [15] Hodge and Mattick [51] Lashway et al. [80]

Table 2

Trends in application of propulsion (prop) and power supply (PS) architectures.

Architecture	Applications	Future applications	References
Mechanical propulsion	Cargo vessels and crew suppliers Naval vessels Tugs and yachts	Cargo vessels and crew suppliers Naval vessels Tugs and yachts	Baldi et al. [29] Van Spronsen and Toussain [28] Vrijdag et al. [104]
Electrical propulsion	Cruise ships Capital naval vessels Offshore vessels Drilling vessels and crane vessels	Cruise ships Capital naval vessels	Vie [39] and Moreno and Pigazo [38] Sears et al. [55], O'Rourke [52] Vanderpump et al. [53] Loyd et al. [54]
Hybrid propulsion	Warships and Patrol Vessels Tugs Long range offshore vessels	Warships and Patrol Vessels	Castles and Bendre [67], Sulligoi et al. [68], and Geertsma et al. [105] Wijsmuller and Hasselaar [69] Barcellos [8] and MER [9]
Electrical prop. & electrochemical PS	Submarines	Submarines Ferries	Sattler [73] and Psoma and Sattler [74] Van Biert et al. [72]
Electrical propulsion & hybrid power supply	Tugs Ferries	Drilling vessels Crane vessels	Volker [10] and Breijs and Amam [12] Rampen and Breijs [13] Ovrum and Bergh [78]
Hybrid propulsion & hybrid power supply	Tugs Yachts	Tugs Yachts Cargo ships	van Koperen [98], Drijver [96] Grimmelius et al. [97] Dedes et al. [79]
Electrical propulsion & DC hybrid power supply	Yachts Offshore vessels Ferries Naval Vessels	Cruise ship Naval vessels Drilling vessels Heavy crane vessels Dredgers	Bosich and Sulligoi [14] Zahedi and Norum [18] Zahedi et al. [17] O'Rourke [52] and Doerry et al. [102] <i>MV Jaguar, Edda Ferd, Dina Star</i>
Hybrid propulsion & DC hybrid power supply	Yachts	Warships Patrol vessels Tugs Long range offshore vessels	van Loon and van Zon [32]

nance. This reduction has prompted DC application in yachts, offshore vessels and ferries. Moreover, some naval vessels use electrical propulsion with DC hybrid power supplies to generate pulsed power for high energy weapons.

Initial research suggests DC power supply supported with energy storage can save 10–15% fuel, reduce CO₂ emissions and improve engine loading, at the cost of a slight increase in NO_x emissions, due to reducing engine speed in part load. These benefits could well lead to the application of DC hybrid power supplies for electric propulsion in cruise ships, capital naval vessels, drilling vessels, crane vessels and dredgers in future. Furthermore, DC power supply seems equally applicable to hybrid propulsion architectures. Therefore, warships, patrol vessels, tugs and long-range offshore vessels appear promising applications for DC hybrid power supply with hybrid propulsion.

8.2. Control strategies

Table 3 lists existing control strategies and their applicability to different power and propulsion systems. Furthermore, this table summarises the benefits of these control strategies.

The traditional method to control ship speed is to perform speed control for propulsion. The operator requests an engine or motor speed setting, which behaves linearly to ship speed, and the control system either injects fuel or switches power electronics to achieve this speed setting [35]. However, in dynamic circumstances, due to wind and waves, this leads to load fluctuation that particularly burdens mechanical propulsion engines and leads to higher maintenance cost [30]. To reduce engine torque fluctuation, torque or power control can be applied as demonstrated in Geertsma et al. [105] and proven for electrical propulsion in Sørensen and Smogeli [63,62].

Alternatively, the following three alternative methods for propulsion control with CPP can also reduce engine overloading.

First, combinator curve control with CPP can reduce static engine loading and provide accurate manoeuvring. Unfortunately, the combinator curve is usually only designed for the propeller curve in design conditions. Overloading can still occur in off-design and dynamic conditions, and the working point of the diesel engine is not optimised for the specific operating conditions at a certain moment in time. Secondly, an H_{∞} optimal controller can reduce dynamic engine loading and increase manoeuvrability [28]. Although this strategy significantly reduces dynamic engine loading and increases manoeuvrability, its performance is optimised for minimising speed fluctuation as opposed to minimising engine load fluctuation, which does more damage to the engine. Moreover, this strategy only allows one performance criterion to be optimised and, therefore, does not allow control that adapts to changing ship functions. Finally, the *angle of attack* control strategy governs propeller pitch to achieve the effective angle of attack on the propeller blade that minimises the risk of cavitation. Sea trials have demonstrated that this approach effectively reduces cavitation, improves manoeuvrability and reduces engine overloading [27].

For AC and DC hybrid power supplies on ships, droop control is the most promising primary control strategy, due to its robustness and scalability, also for zonal distributed power supply. Secondary heuristic control strategies can achieve fuel consumption and emission reductions and a zero-emission operating mode. However, literature from maritime and automotive applications suggests that further fuel consumption and emission reductions can be achieved with a tertiary ECMS control strategy. Application of ECMS strategies on ships has demonstrated fuel consumption can be reduced with 5–10%. Further research is required to determine whether other important criteria can be improved with this strategy as well.

Finally, the application of DC power supplies has enabled running the generator at variable frequency, reducing fuel consumption.

Table 3
Control strategies.

Control strategy	Applicable architecture	Benefits	References
Speed control	Mechanical, electrical and hybrid propulsion	Minimum speed fluctuation	Van Spronsen and Toussain [28]
		Prevent over-speed Robust control strategy Intuitive relation with ship speed	Guillemette and Bussi�eres [30] Xiros [36] Vrijdag [27] and Vrijdag et al. [104]
Torque and power control	Mechanical, electrical and hybrid	Reduced fuel consumption Improved thermal loading	Faber [33] and Stapersma et al. [34] Smogeli et al. [63], Sorensen and Smogeli [62], and Geertsma et al. [105]
Combinator curve control	Propulsion with CPP	Prevent static engine overloading Accurate manoeuvring	Vrijdag et al. [37] Stapersma and Grimmelius [35] and Geertsma et al. [105]
Optimal speed and pitch control	Propulsion with CPP	Reduced dynamic engine loading Increased manoeuvrability	Van Spronsen and Toussain [28] Xiros [36]
Angle of attack control	Propulsion with CPP	Reduced noise Increased manoeuvrability	Vrijdag [27] Vrijdag et al. [104]
Electric motor assist	Hybrid propulsion	Improved Manoeuvrability Reduced loading and increased top speed	Topaloglou et al. [71]
Frequency droop and isochronous control	AC power supply	Effective load sharing	Mahon [56], Karim et al. [58]
		Splitting load dynamics	Amgai and Abdelwahed [59] Seenumani et al. [60]
Heuristic control strategies	AC & DC hybrid power supply	Different operating modes Zero emission mode	Sciberras and Norman [95] Karim et al. [58]
ECMS strategy	AC & DC hybrid power supply	Reduced fuel consumption and emissions Optimisation of other criteria	Rampen and Breijs [13] and Breijs and Amam [12] and Vu et al. [93] Grimmelius et al. [97] and Shi et al. [92]
Voltage droop load sharing	DC hybrid power supply	Splitting load dynamics Reduced engine loading	Sulligoi et al. [68] Zahedi and Norum [18]
Optimum load levelling	DC hybrid power supply	Reduced fuel consumption Engine Loading Emissions Noise and vibrations	Ovrum and Bergh [78] Zahedi and Norum [18] Zahedi et al. [17]
Secondary MPC	Hybrid propulsion and hybrid power supply	Handle conflicting requirements	Park et al. [103] and Haseltalab et al. [94]
		Handle unknown future conditions	Grune and Pannek [107]

tion, engine loading, emissions, noise and vibrations. Various optimisation strategies, as the one proposed in Zahedi et al. [17], can achieve significant improvements over various criteria and allow trade-offs between these criteria. Furthermore, MPC can be used for a control strategy that trades off conflicting performance requirements, both for known and unknown future operating profiles [103,93,94].

9. Research opportunities on control strategies for smart ships

Technological advances in hybrid power and propulsion systems could meet the challenges for smart ships, as discussed in Section 1. However, in many cases, the control strategy is vital to improve and maximise performance. Further research into these control strategies is required, with a holistic approach, and in three directions:

- Control of the mechanical drive train for mechanical and hybrid propulsion architectures;
- Control of the electrical machine in hybrid propulsion architectures; and
- Control of hybrid power supplies for hybrid and electrical architectures.

9.1. Control of the mechanical drive train

The control challenge of the mechanical drive train is twofold:

- Reduce the impact on engine fuel consumption, thermal and mechanical loading due to load fluctuation from waves and manoeuvring; and
- Control the CPP to optimise the static working point for fuel consumption, emissions, vibrations and static engine loading and the dynamic behaviour for cavitation noise, manoeuvrability and dynamic engine loading.

We have identified three potential strategies to resolve these challenges.

9.1.1. Torque control

Current control strategies for mechanical propulsion all rely on some form of speed control. Although disturbance attenuation can be reduced with advanced speed control strategies, results remain limited [28,30,36]. Another approach is to regulate thrust with torque or power control. With this approach, disturbances would cause more shaft speed fluctuation, while oscillation in engine loading would be reduced. However, shaft speed fluctuation would remain limited as the mechanical propulsion plant has a strong

self-regulating performance as demonstrated in Guillemette and Bussi eres [30]. Thus, the strategy could lead to better thermal loading and reduced fuel consumption, as was shown with limitedly validated models in Geertsma et al. [105] for mechanical propulsion and with models and experiments in Sorensen and Smogeli [62] for electrical propulsion. On the other hand, the controller would have to maintain constraints on fuel injection, over- and under-speed and would require torque measurement. Vrijdag [27] described a test set-up on a RNLN M-class frigate, which used accurate thrust measurement based on optical sensors that can measure shaft deflection up to nanometer accuracy. This thrust measurement, or an equivalent torque measurement device, could be used for this control strategy. For an architecture with hybrid power supplies, torque control would also allow a power setpoint to be used. Then, an optimisation strategy could calculate the optimum load share, in power, between various supplies, for example the main engine, a diesel generator and a battery. Whether this could lead to a stable control strategy needs to be investigated thoroughly.

9.1.2. Adaptive combinator control

A CPP allows the static operating point to be moved to another point in the engine operating envelope, while maintaining the speed setting (see Fig. 9). This would influence various performance criteria, such as fuel consumption, emissions, vibrations and static engine loading. A controller could be developed that defines the optimal pitch setting from the optimal static operating points resulting from the minimal weighted cost function of numerous criteria such as the ones mentioned above. However, in order to determine optimal pitch under operational conditions, the control strategy would have to account for uncertainty and for disturbances, most importantly due to waves. *Model Predictive Control* (MPC) can take both these effects into account [93,103,94]. Furthermore, MPC could also be used to determine the optimum trajectory over a certain future time period, for example during an acceleration manoeuvre [94,106,107].

9.1.3. Angle of attack and torque control

The *angle of attack* control strategy can demonstrably reduce cavitation and improve acceleration performance [27], but the impact of the angle of attack control strategy on dynamic engine loading has not been investigated yet. However, the angle of attack strategy could be combined with torque control, to achieve stabilised torque and fuel injection. This combined control strategy could be used for a trade-off between various objectives, such as cavitation, manoeuvrability and dynamic engine loading. However, the impact of this control strategy on the static working point of the diesel engine needs to be investigated, because this working point determines fuel consumption, emissions, vibrations and static engine loading.

Furthermore, a trade-off could be made between dynamic performance improvements with the angle of attack control strategy and static performance improvements with adaptive combinator control. This could be achieved by adding the estimated angle of attack, as proposed by Vrijdag [27], as one of the performance indicators for the proposed Model Predictive Controller. Alternatively, this controller could impose constraints on the angle of attack, in order to prevent cavitation. For smart ships this constraint could, for example, only be imposed if cavitation noise has priority over other criteria.

9.2. Control of electrical drive in hybrid propulsion

Hybrid propulsion allows the electric motor to be used in parallel with the main engine, either with the motor providing torque in

electric motor assist mode or with the motor operating as a generator in *power take-off mode*. Thus two control strategies could be developed for hybrid propulsion.

9.2.1. Electric motor assist

In most current applications or proposals for hybrid propulsion, the electrical machine is switched off during mechanical drive. Topaloglou et al. [71] have demonstrated that electric motor assist can reduce the thermal loading on the propulsion diesel engine, with a control strategy that is aimed at reducing the air excess ratio of the main engine. A control strategy with the electric motor running in speed control and the engine supplying constant power in torque control, could potentially achieve this as well. Alternatively, a Model Predictive Controller providing torque setpoints for both the electric motor and the diesel engine with a performance indicator that heavily penalises torque fluctuations on the engine, might also achieve this. However, research would be required whether the computational speed of such an MPC strategy would be fast enough to keep the time period between discrete control actions small enough to maintain robust control.

Because AC electric generators always run at full speed, they could provide additional power more rapidly than the mechanically connected engine, as this engine runs on the propeller curve speed and has limited engine margin. Moreover, batteries could improve dynamic performance without increasing dynamic loading on the diesel generators. Thirdly, running the electric motor in electric assist mode could enable a reduced engine rating, particularly when maximum power is only required infrequently, as is the case on tugs.

In order to achieve reduced dynamic loading of the diesel generator, the optimised load sharing strategy with batteries could be used, as proposed in Zahedi et al. [17]. However, this approach can only be applied to DC power supplies. Alternatively in AC power supplies, the load sharing could be controlled by similarly optimising speed droop settings. Whether this could lead to a stable control strategy, which particularly also prevents overloading of any of the diesel generators, requires further research.

9.2.2. Power take-off

With the proposed shaft generator control strategy, the dynamics of load transients in the electrical systems are equally shared between diesel generator and shaft generator. Alternatively, if only the shaft generator or the diesel generator should handle the load transients, this could be achieved by running that generator(s) in isochronous mode and the other generator(s) in droop mode (see Section 3). In the configuration with a large propulsion gas turbine, load transients on the diesel generator could potentially be limited with this strategy. Moreover, hybrid power supplies could supply the load transients from batteries. However, further research would be required to determine whether this could lead to a stable and robust control strategy.

9.3. Energy management of hybrid power supplies

Hybrid power supplies enable sharing the total instantaneous load between different types of power source, typically diesel engines and batteries. This is referred to as *energy management*. In particular, ECMS has shown to be a very promising energy management strategy.

9.3.1. ECMS

In the automotive industry, the ECMS strategy has shown to achieve the best results in minimising fuel consumption over an unknown operating profile. Applying ECMS to power systems on ships has been proposed in Grimmeli us et al. [97]. Moreover, appli-

cation of ECMS on ferries and tugs has shown significant reduction in fuel consumption of 2–11% [93,12].

9.3.2. ECMS with receding horizon

When the distance or time of the remaining operating profile is known, the required final battery charge could be accounted for in the control problem with a reference state of charge that becomes smaller over time. This is referred to as the ECMS approach with receding horizon and could ensure the full battery capacity is used during the operating profile. Fuel consumption of this strategy, if well defined, could approach the optimal fuel consumption calculated with an off-line strategy, such as dynamic programming or the Euler-Lagrange optimal control formulation [11].

9.3.3. ECMS strategy for multiple performance criteria

The ECMS approach has been developed to minimise fuel consumption. Many other criteria covered in Section 1, such as noise, vibrations, emissions or engine maintenance also primarily depend on the engine (and battery) operating point determined by the power setting of the power source. Therefore, similar cost functions as a function of power setting could be derived for these criteria as well and the overall optimal power setting could be determined from a weighted cost function over multiple criteria. Thus, using ECMS for multiple criteria could be a promising approach to improve performance over multiple functions for future smart ships.

9.4. Integrated control approach for flexible mission context

Ultimately, the control strategies proposed for further research should be combined. A schematic overview of the potential overarching control strategy for such an integrated system with hybrid propulsion and hybrid power supply feeding a DC power system is illustrated in Fig. 24. Significant research is required to establish the feasibility of such an integrated approach.

10. Conclusions and recommendations

This paper has reviewed current and future power and propulsion system architectures and their associated control strategies for smart ships. The variety and complexity of these architectures poses an increasing amount of design choices to the ship and control system designer. In order to determine the optimal architecture, knowing the operational profile is essential.

First, hybrid propulsion is economically beneficial if the ship sails below 40% of its top speed a significant amount of time. Furthermore, hybrid power supply is beneficial when the total electrical load has a great spread over time and can improve availability and reduce noise. Finally, DC power systems potentially bring down conversion losses and can run the generator at variable speed, reducing fuel consumption and associated emissions with up to 20%.

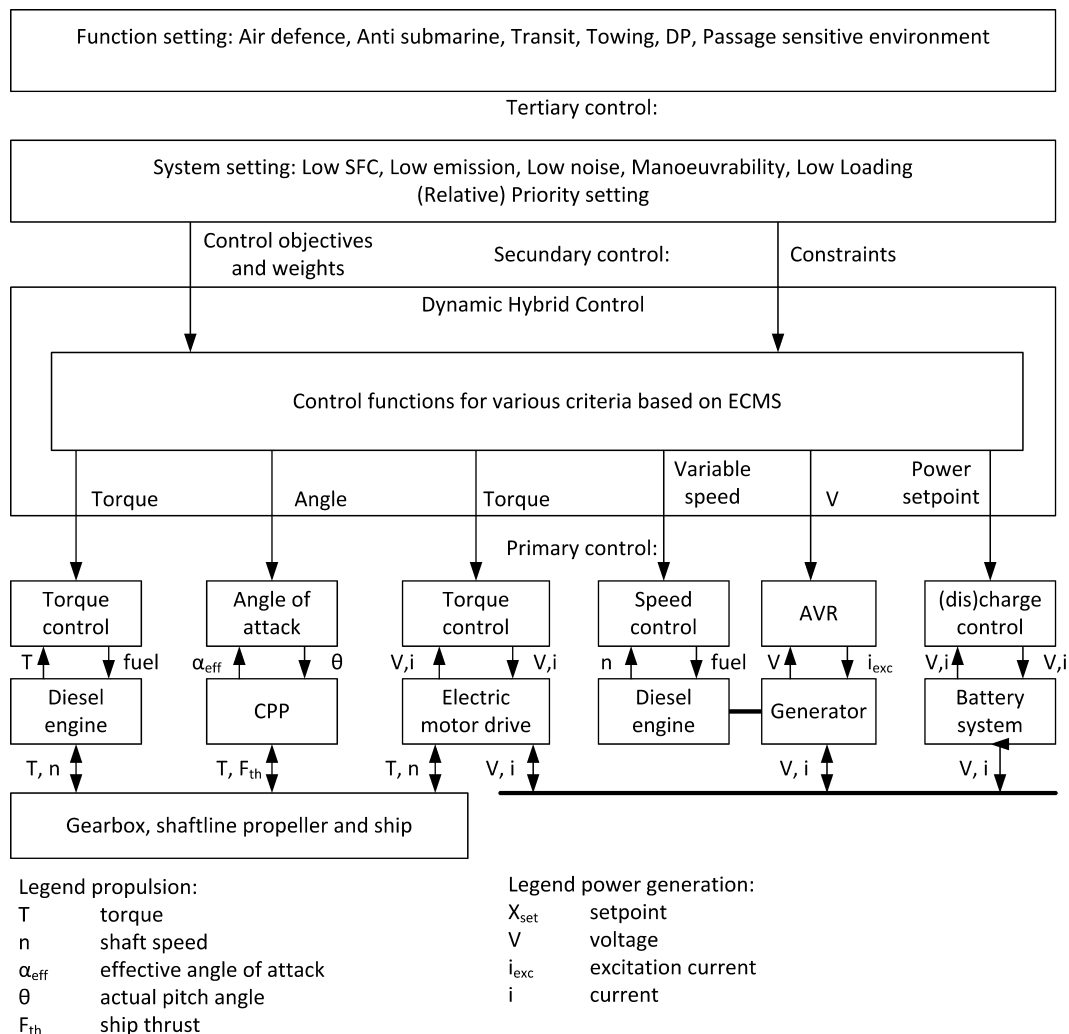


Fig. 24. Schematic presentation of future integrated control strategy.

One of the most important aspects that determine whether the full potential of the selected architecture can be achieved in practice is the control strategy. As such, many intelligent control strategies have been investigated and applied in other applications such as the automotive industry and land based micro-grids. However, advanced control strategies have only most recently been investigated and applied in maritime applications, and only reductions in fuel consumption and emissions, of 15–35%, have been quantified for some cases, which is partly achieved by recharging batteries from the grid. Improvements in other criteria, such as propulsion availability, radiated noise and maintenance cost are crucial for effective hybrid power and propulsion systems as well.

Ultimately, the proposed control strategies should be combined. Moreover, significant research is required to establish the feasibility of such an urgently required, integrated approach. Only the proposed research can deliver the anticipated improvements. This would then enable the design of smart ships that can perform multiple functions effectively, efficiently and environmentally friendly in the ever so complex maritime environment.

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