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Optimising design and power management in energy-efficient marine vessel power systems: a literature review

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ABSTRACT
The conventional marine vessel power systems typically have the potential to improve their fuel consumption and their emissions. This can be done by redesigning the system configuration, the machinery and the power management strategy. The addition of options in power management allows for the running of individual power sources closer to their optimal operating point. However, this immediately raises questions about how to redesign the system and how to operate it to maximise the benefits. The information needed to answer these questions is often scattered around separate sectors of the marine industry. The system integrator needs to be able to combine the complex dependencies of these individual sectors to formulate the big picture that describes the whole power system. Numerical optimisation algorithms provide solutions to develop methodologies to solve multi-variable and potentially multi-objective problems. This literature review presents the authors' findings of design and power management optimisation cases in marine vessel power systems.

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1. Introduction

Marine engineers have been motivated to replace the conventional power systems in marine vessels with complex power systems to adjust for tightened emission legislation and to reduce operational costs. Here, the power system includes the propulsion, the electric and the auxiliary systems. This type of trend is already familiar in the automotive industry, electric power production and the heating and cooling industry to name a few. Hybridisation has the greatest potential with vessel types that have a variant operational profile, are powered by a single prime mover, such as an internal combustion engine (ICE) and that have, by conventional design, a simplified powertrain configuration, referred to as topology, to enable options to be added in the power management with reasonable justification. The potential also exists, although in lesser quantity, with more complex power systems of modern day.

A system integration designer who is responsible for the vessel power system must ask the question if the hybrid power system is the correct solution. The additional investment cost of a complex system architecture should be paid back with the lower operational costs in a reasonable time. The following defining questions arise:

- Can the system be retrofitted or should the whole power system be redesigned?
- Which system topology should be used?
- How big should the battery pack be?
- Can a smaller main engine be chosen?
- What is the lifecycle of the power system?
- When should the battery be charged/discharged?
- Is it possible to charge the battery from the land grid?
- What if the propulsion load is 5% higher?

These questions are often answered by choosing a system topology, sizing either the retrofitted components or the whole machinery system and using a rule-based power management strategy to find the potential improvements in the system's performance. However, if the same system output can be generated with multiple different control combinations, then which combination will best achieve the defined goals? The different levels in the system design are choosing the system topology, sizing the components and controlling the components and they all depend on each other, as explained in Guzzella and Sciarretta (2007). Thus, the design problem should be solved as a nested problem as suggested also in Silvas (2015). The solution to this multi-level problem

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depends on the intended operation of the vessel. The operation of the vessel in a time frame is referred to as a duty cycle.

In numerical optimisation problems, the interesting system outputs are described with an objective function. The objective function value is dependent on optimisation variables. The optimisation algorithm observes the behaviour of the objective function and tries to find a set of variable values that minimise or maximise the function value. In colloquial language, the system is optimised with a parametric variation study using a subset of interesting parameters of the system. While this kind of brute-force search (BF) is useful in certain cases, for hybrid power systems, the high number of design variables and the fineness of the search grid makes BF computationally exhaustive. To find the minimum/maximum faster, a numerical optimisation algorithm follows either the given objective function gradients or tries to estimate the gradients. Additional definitions for the problem, called constraint functions, can also be defined. In the case of a hybrid power system, the objective function is most often formulated to minimise fuel consumption. Sometimes additional targets, such as emissions and investment costs, are also included. The constraints typically set a demand for the total delivered power which must be higher than the load. In addition, operational limitations of individual components are described with constraint functions. Although numerical optimisation is a useful tool for system design, Edgar et al. (2001) emphasise the importance of choosing the correct algorithm for the problem at hand. Otherwise, the problem must be formulated to make it suitable for the available algorithm. The demand for finding the solution online and in real-time also affects the choice of methodology.

This article presents a review of studies where either the power management or the power system design was optimised using numerical optimisation algorithms. Current system solutions are described in Section 2. Section 3 presents the optimisation cases in which only the system power management was studied. This is followed by Section 4 in which the component sizing is included in the optimisation problem. A selection of existing power system design tools are presented in Section 5. Projections for future work and the conclusions are discussed in Sections 6 and 7, respectively.

2. Increasing options for power management in a vessel power system

In conventional diesel-mechanical (DM) propulsion systems, each propeller is mechanically linked to a propulsion engine, and the engine is designed according to a maximum propulsion load. Many vessel types, such as the tugboat, spend the majority of their time on part load as shown by Cavalier and Caughlan (2009). This means that the propulsion engines run close to the optimum point for only a short time.

In the 1990s, the diesel-electric (DE) propulsion systems emerged from various system designers. The main difference in the system architecture was that the mechanical power was converted into electric power and then back to mechanical propulsion power. One large diesel engine could be replaced with a number of smaller gensets, which not only provided power to the propulsion system, but also to the auxiliary system. Part of the gensets can be shut off under low propulsion loads, making the active gensets run closer to their rated power. Although this additional degree of freedom in power management enables running the gensets at more fuel-efficient operating point, the conversion losses in the generators and the variable-speed drive (VSD) lower the overall system efficiency (Ådnanes 2003; Molland 2011; Babicz 2015).

By definition – a hybrid powertrain includes more than one type of energy storage system (ESS) and power plant for meeting the needs of a power consumer. The basic technologies for ESS are presented in Baseley et al. (2007), Ibrahim et al. (2008), Lukic et al. (2008). The application determines whether a good specific energy density of modern batteries is needed or if high power density storages, such as a hydraulic accumulator and a supercapacitor, are more beneficial. For example, the chosen technology in electric machines (EM) and batteries affects the investment cost and profitability as discussed in Reed (2015). Currently, the combination of combustion engine and electric battery is the most familiar hybrid technology because of the automotive industry. In the marine industry, the definition of a hybrid power system is different. Power systems that utilise different fuels in a single engine or combine the DM and DE configurations are sometimes called hybrids.

The common goal in a hybrid drivetrain is to operate the primary power source at the optimum point as much as possible. This is done using the secondary energy source to cover the difference between the operating point of the primary power source and the power consumer as explained in Hawksey (2014). For a combustion engine, even balancing the oscillating load coming from the waves is beneficial, even though the optimum operating point may not be reached.

Figure 1 shows the typical topologies in a hybrid propulsion system. The functionalities and characteristics of the series and parallel topologies are explained in NSBA (2015). From a design point, the main difference is that the EM in a series topology need to be able to cover the maximum power demand, while

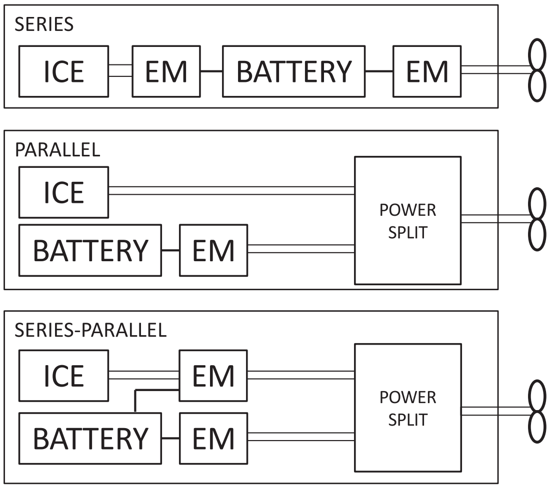

Figure 1. Hybrid topologies using a combustion engine and a battery.

in parallel topologies the EM can be sized for lower power levels. In parallel topology, the engine can feed the propulsion loads without additional electric conversion losses, which is beneficial under high propulsion loads. The series–parallel topology combines the features of both the series and parallel topologies. While enabling an asymmetric sizing of the EM and having a redundant EM for electric propulsive power, the increased number of components increases the investment cost.

The design problem in marine hybrid power systems is similar to the system in a hybrid electric vehicle (HEV). The main difference is the environment that the marine applications work in. On-land vehicles tend to operate in environments in which the interaction with the surrounding traffic is more frequent. In general, marine vessels operate in open spaces with less traffic, which means that the machinery controls are less transient. The hydrodynamic interactions between the water, the propeller and the vessel hull affect the propeller operating as described in Ghose and Gokarn (2004). In practical designs, these interactions lead to fairly low dynamics between the machinery operating point and the actual vessel motion. Therefore, the static propeller loads are sufficient in system modelling in most cases as stated in Vu et al. (2015). Due to the hydrodynamics of the propeller, the ability to recuperate energy efficiently using regenerative braking is a feature that is typically missing in marine vessels. Although use of an ESS would allow regenerative braking, it is not a highly interesting option due to the poor efficiency of the propeller when working as turbine. Unlike cars, marine vessels typically have more than one combustion engine in the power system. Although the conventional DM topologies can generate electric power with the propulsion engines, there are typically diesel fuel-powered gensets onboard as well. By linking the multiple power sources to form a hybrid power system, a designer has more flexibility to optimise the power management in the system.

The feasibility of using a hybrid power system for different vessel types was studied by Dedes et al. (2012), Völker (2013), Díaz-de Baldasano et al. (2014), Andersson and Logason (2015), NSBA (2015) and Yum et al. (2016). The service life of the battery, availability of shore power, vessel size and chartering commands and use of generated heat were found to influence the feasibility of the hybridisation depending on the vessel type.

3. Power management optimisation makes the best use of existing components

The target when using parallel options for power management is to know how to split the load between the parallel power sources. This target is eminent not only for hybrid power systems but also for DE configurations. There is an additional dimension if a single component can deliver the same output with different system states; an example of this is if the controllable pitch propeller is capable of generating the same thrust with different combinations of rotational speed and pitch angle. Alternatively, in a DC grid, the generators do not have to run at the same fixed speed to maintain the required voltage level in the grid. In addition, the optimisation problem in power management has one more degree of freedom when one of the energy sources has a limited capacity compared with the other sources. For example, the battery in a hybrid power system typically has a smaller energy capacity compared with the capacity on the combustion side. The maximum and minimum limits of the SOC introduce time dependency in the power management optimisation which sets the question whether the battery should be charged or discharged at the current moment of time? A recent literature review by Geertsma et al. (2017) presented findings on different system control strategies categorised by the vessel system topology. Before the actual system design is optimised, the power management optimisation is studied with a pre-defined system topology consisting of a set of pre-chosen components.

Baldi et al. (2016) used the mixed integer non-linear programming method to optimise the load sharing in a hybrid power system without batteries. Combining sequential quadratic programming for the continuous variables and using the branch and bound method for the integer variables, the problem was solved with Matlab. A cruise ship was used for the case study. The shaft generator/motor was sized for the hybrid power system by trying out different unit sizes. The hybrid system involved lowered operational costs especially when the dissipated heat from the main engines was utilised in the ship's heating system. The investment costs and payback period, however, were not considered.

The integrating element of a rechargeable energy storage with capacity limits brings a time aspect to the problem. Vu et al. (2014a,2014b,2015) presented variations of a power management optimisation method using a series hybrid tugboat. The penalty function included elements for fuel consumption, load demand tracking and changes in battery energy. A genetic algorithm (GA) was used for the search. Studies compared algorithms when the duty cycle was known beforehand and if the duty cycle was unknown, but could be predicted based on the statistical and repetitive nature of the tugboat duty cycle. Compared with the rule-based power management strategy described in Sciberras and Norman (2012), 9% fuel savings were obtained with the optimised machinery usage. The difference between the predicted duty cycle and the known duty cycle was less than 0.5%.

Zahedi et al. (2014) studied the fuel savings in a series hybrid off-shore support vessel with a DC grid. The proposed power management strategy charges and discharges the battery between the minimum and maximum capacity in a repetitive cycle. If the pulsed cycle of this square wave-like usage becomes infeasible, a so-called continuous mode is engaged, where the SOC oscillates in a smaller range to even the load oscillation at the active diesel generators. Using a simulation model from Zahedi and Norum (2013), they showed that with the proposed algorithm, the DC grid series hybrid leads to 15% fuel savings compared with a conventional DE configuration with an AC grid and 7% fuel savings compared with a DC grid configuration without a battery. The BF algorithm was used to find the optimum operating point for the generators under a dynamic load. Both online and offline algorithms were proposed; the online version of the algorithm uses a search space with less points for faster computation and a low-pass filter to estimate the average load and the load ripple.

Haseltalab et al. (2016) expanded the power management problem with a velocity tracking error, and used a model predictive controller (MPC) to minimise both the velocity tracking error and the fuel cost in the load-sharing optimisation case. Using the simulation model from Zahedi and Norum (2013) with a combination of battery and an ultra-capacitor as the energy storage, the feasibility of the MPC under surge conditions was shown. The actual algorithm for the numerical optimisation or performance improvements to a reference system was not presented.

A battery hybrid tugboat with a parallel topology was studied by Grimmelius et al. (2011). Two cost functions were compared side by side to find the global minimum for the problem: one for the mode which the EM works as a motor and one which EM works as a generator. Despite evaluating two separate cost functions, a good potential for real-time implementation was obtained with a linearised controller, and utilising linear programming and the Simplex optimisation method in Matlab/Simulink. The cost function in the used equivalent cost minimisation strategy (ECMS) includes the cost of energy stored in the battery; thus, the future use of the battery is considered. The study did not present a comparison to the baseline system.

Bassam et al. (2017) compared different energy management strategies for a hybrid passenger vessel powered by fuel cells and a battery. The authors' multi-scheme strategy was a combination of the other strategies reviewed in the comparison. A Simscape and Matlab environment was used for system modelling and optimisation. The duty cycle of the studied passenger vessel was fairly flat excluding the docking phase with higher load peaks and the acceleration phase with a higher and wider power peak. The size of the battery and the energy management strategies that were used, led to a small variation in the battery SOC during the operation excluding the charge-depleting–charge-sustaining (CDCS) strategy. The battery was charged to the initial SOC using shore power after the daily shift. Including the battery charging cost, the total operating costs of the different energy management strategies were reported to be similar, although most cases favoured the ECMS strategy over the developed multi-scheme strategy. This occurred even when the sensitivity towards energy prices was considered. The search algorithm used and the baseline results of the vessel powered by the fuel cells alone were not reported. The results imply that the chosen lead-gel battery might not be ideal for the duty cycle of the studied vessel with high power and low energy transients.

As a bridge between Sections 3 and 4, the Master's thesis by Kwasieckyj (2013) is briefly reviewed. Proposing a design methodology built with MS Excel, four different vessel types were studied that had the potential to apply the hybrid power system. However, in this case, the use of battery was not included in the hybridisation. For each vessel type, the author handpicked a number of different machinery topologies that enabled load sharing between parallel power sources. The load share was optimised using the generalised reduced gradient search algorithm. Because this is an algorithm for finding a local optimum, a set of initial guesses was pre-selected for each topology for a more complete coverage in the search space. The objective function included the fuel consumption of the combustion engines, while the constraint function ensured that the load demand is met with machinery operating within the specified limits. Although the actual power system design was not optimised, this research studied a small subset of possible system topologies. In addition, it considered the sensitivity of the solutions with changes in the operational profile, component efficiencies and control strategy. Although the investment cost was not included in the formulation of the optimisation problem, it was estimated for the compared topologies.

4. Increasing the frame size in the optimisation problem: solving the sizing problem

On a general level, minimising the fuel consumption tends to decrease the load share of the combustion side and increase the load share of the electric side. However, this means that the components in the electric side would have to be sized for a higher rated power and capacity, which would lead to larger, heavier and more expensive electric components. Thus, the two objectives of fuel efficiency and sizing conflict with each other. Two formulation approaches are typically used for a multi-objective sizing optimisation: a penalty function that weighs these two objectives and leads to a single optimum just as in the previous power management optimisation cases, or the solutions are ranked in groups based on their fitness towards the problem. The results of the latter approach are often presented in Pareto fronts, shown in Figure 2 in which the best solutions get the smallest rank. Within each rank, all solutions are equally as good as the other solutions. Therefore, the final decision needs additional information that is either not available or is not used for input when the problem is formulated.

Component sizes affect the objective function and the constraints set for the typical power management optimisation problem. Reflecting cases presented in Section 3, the size of the combustion engine defines the fuel consumption rate, which is typically included in the objective function to be minimised. The fuel consumption rate for an engine is specific for each size, but often simplified using a generic specific fuel consumption (SFC) chart in which the fuel consumption rate is scaled with the rated power. The capacity of the battery typically affects the constraints of the problem; since the battery is a time-integrator element, the capacity defines when charging or discharging should be done and the magnitude of charging. Optimising the component sizing requires that the individual component sizes are set as optimisation variables.

Solem et al. (2015) presented a design optimisation study for a vessel with a DE topology. Although this was not a hybrid system per se, it was a good example of simplifying the system characteristics to find a global

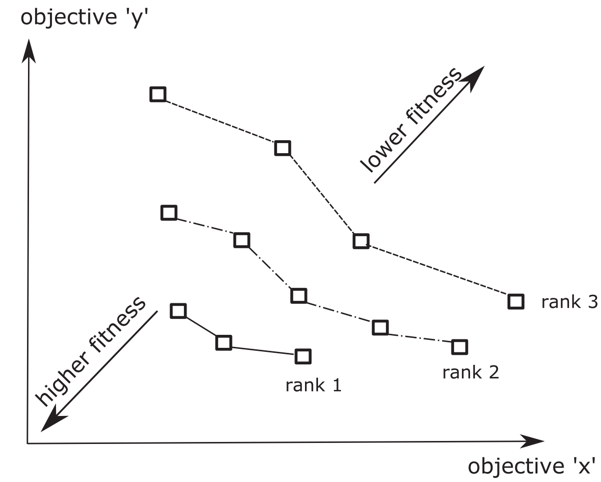

Figure 2. Pareto optimum of a generic multi-objective optimisation problem.

solution for the multi-objective optimisation problem. The diesel generators of a small size anchor handling vessel were sized using the branch and bound method, and the cost function, which included penalties for fuel cost, investment cost, NOx taxes and the area required for the installation. The use of special ordered sets of type 2 (SOS2) guaranteed that a global optimum could be found when using piecewise linear fuel consumption data to model the diesel engines. Using engine data of multiple models from multiple manufacturers, the study pointed out, that with the used penalties the objective function typically becomes flat and the feasible engine model selection is large. This means that the solutions become more sensitive for the stopping criteria for the algorithm.

Del Pizzo et al. (2010) presented two different design methods for sizing the main components in a series topology hybrid system. The methods were designed according to the primary power source operation type. Both methods were formulated to sustain the battery SOC; the final SOC was the same as the initial SOC over the studied vessel duty cycle. An evaluation was carried out for a hybrid waterbus using the exhaustive search method. Discrete parametric variation of the ratio for the maximum and average generator power showed that for the estimated duty cycle of the waterbus, a minimum fuel cost was obtained with a ratio of 1.15.

Dupriez-Robin et al. (2009) used the so-called power modelling method for sizing the main components in a sailboat. The sailboat incorporated a series topology in the electro-mechanical driveline, which was complemented with a parallel wind energy source (the sails). The optimum power management was then searched by formulating a discrete search space with dynamic programming (DP). Using DP, a global optimum was found for the power management problem. The authors recognised that uncertain wind conditions had a strong influence on the optimum solution. Thus, test cycles with varying wind conditions were studied. It was suggested that this optimisation method could be further refined by studying the neighborhood of the found optimum with local optimisation routines. No comparison to a baseline system was reported.

Studying a series hybrid of a DC grid type, Soleymani et al. (2015) optimised the sizing of the machinery. A particle swarm optimisation (PSO) algorithm was used for rightsizing a combustion engine, generator, electric motor and battery pack. The objective function only included the fuel costs over the studied duty cycle. The constraint function included penalties for the vessel operational requirements (maximum acceleration, acceleration time and maximum velocity). A simple thermostat control strategy was used to switch the combustion engine on and off based on the battery SOC, in a similar way used by Zahedi et al. (2014). Continuous scaling factors were used for the fuel consumption and the efficiency maps of the main components leading to a continuous optimisation space. An interesting result in the sizing was that, although no penalty was used for the component space requirement or mass, the optimum solution did not maximise the battery capacity. With optimised component sizes, the authors reported a considerable fuel consumption saving compared with the baseline system. After finding optimum sizes for the components, the control strategy was further refined with a combined thermostat-fuzzy logic controller. The improved PSO-fuzzy controller was only used to refine the power management and it did not contribute in the sizing optimisation routine.

Sciberras and Grech (2012) and Sciberras and Norman (2012) studied a motor yacht with parallel topology to find an optimum solution between the two conflicting objectives of fuel consumption and physical size of the system. Instead of continuous scaling of the components as done by Soleymani et al. (2015), the authors used a database of discrete components for a more real-life selection of available components. Using a rule-based control strategy, the control values for the components were set based on the velocity demand, battery SOC and the operating limits of the components. For this non-linear and discontinuous problem, non-dominated sorting genetic algorithm (NSGA-II) and Pareto ranking were used. An interesting finding was that all feasible solutions had the same ICE as the original baseline system. This is likely because the duty cycle is fairly flat with one larger energy peak; the electric drive with higher rated power and larger battery capacity was penalized heavily if this energy peak was to be covered in the electric assist mode.

A similar study to the one by Sciberras and Norman (2012) was reported by Zhan et al. (2015). The test case involved retrofitting a battery pack in a trailing suction hopper dredger in which the diesel engine, the VSD and the battery pack were sized using the NSGA-II algorithm. Retrofitting a parallel hybrid was supported by the fact that the original system already included a shaft generator and that the duty cycle included power peaks for each cycle during the operation. A database of discrete machinery units was used, but in addition to the objective function used by Sciberras and Norman (2012), an additional progressive punishment was used if the minimum limit of the battery SOC was not respected. The interesting outcome in the results is that compared with the fuel consumption and installation weight of the original system, both main objectives improved with solutions in the Pareto front. Although a clear report on the original system component characteristics, such as SFC, efficiencies and rated powers was missing, the results hinted on a successful rightsizing of the system.

Skinner et al. (2009) used a multi-objective GA to design the propulsion system of a nuclear-powered attack submarine. With four mission scenarios, the following propulsion drive topologies were studied: a pure mechanical drive, a direct electric drive, a geared electric drive with multiple parallel electric motors and a parallel geared combination of steam turbine and electric motor (referred to a hybrid). The sizes of the components relevant to each topology, including the propeller diameter, were set as the optimisation variables. Multiple objective functions were formulated to maximise the component efficiencies and to minimise the EM size and total system energy consumption. The results showed the tradeoff characteristics and, since multiple different mission scenarios were studied, the designer was forced to choose which scenario to optimise the machinery. By using a supervisory controller to minimise the combined power loss within the topology, the hybrid topology showed the best energy consumption of the three alternatives. This results from avoiding the poor efficiency of a steam turbine at low loads. The authors recognised the downsides of the physical size of the complex hybrid system along with the fact that the single prime mover in the other topologies could be replaced with multiple smaller ones to improve their energy efficiency.

Wen et al. (2016) studied battery size optimisation in a large oil tanker powered by a combination of photovoltaic solar panels, gensets and a battery pack. The battery balanced the oscillating output of solar panels as the ship moves in the waves. The problem was formulated for the interval optimisation method and INTLAB in cooperation with Matlab was used. The multi-objective problem was solved using weighted penalties for fuel cost, battery installation and replacement cost and the capital recovery factor. In addition to the load demand and component limitations, penalty for the amount of greenhouse gas emissions was included. The article reported that the swinging motion of the ship influences the optimal battery size significantly. Optimal sizing of the battery with the proposed interval optimisation method reduced the net present cost (NPC) of the system by 12% for the chosen operating route. The greenhouse gas emissions were reduced to almost one fourth with an optimum battery size. Lan et al. (2015) studied the same case without the effect of swinging motion, and used a combination of the PSO and NSGA-II algorithms reaching to 24% NPC reduction.

The characteristics of five optimisation algorithms for the design optimisation of a HEV powertrain were summarised in Silvas et al. (2014). In all cases, DP was used to optimise the power management level. The non-linear and potentially discontinuous nature of the design problem requires the use of a global search method. Although the PSO and GA are widely used in design optimisation of hybrid power systems, the fast computation and the reusability without tuning favoured DIRECT algorithm in design optimisation level according to Silvas.

Regarding the optimal sizing of hybrid machinery, a very important point was made by Wen et al. (2016). The ideal target would be to size the machinery for optimum energy consumption. However, in reality, the safety and usability aspects harshly override the load-sharing target. For instance, the diesel gensets in Wen et al. (2016) needed to be sized based on the maximum power demand of the tanker, while only battery size was optimised for the application. Certain vessel types operating in a harbour or near the coast might be more feasible for utilising a limp-home mode, which is not the case with vessels operating far offshore. For leisure boats, it is also crucial to maintain a smooth driver experience under a faulty system condition; it is inconvenient for a boat captain to sail at a reduced speed when the battery is drained or a fault occurs in the electric grid. Another reliability issue with hybrid systems in marine vessels is that the crew needs to be trained to operate and maintain these more complex systems making it more challenging for the boat owners to find skilled people for the crew.

Finally, a comment about the choice of time horizon and the power management strategy should be made. An offline design problem is formulated using a chosen power management strategy and a duty cycle known a priori. Thus, the found optimum is valid only for that particular duty cycle if the chosen power management strategy is used. For example, using a global search method, such as DP, for the optimum power management over the duty cycle, a designer can find the utopia potential of the system. In real life, the decision about the power management is typically based on the present system state or, in sophisticated approaches, the system state is predicted over a definite prediction window (see Figure 3). Since the strategy is different, the real-life application is not capable of delivering the same performance as the offline design even if the offline model would otherwise be an ideally accurate description of the system. Although offline strategies are not directly realisable in real-life application, they are useful in providing a benchmark solution and they can be modified to be used in online strategies, as stated in Waschl et al. (2014).

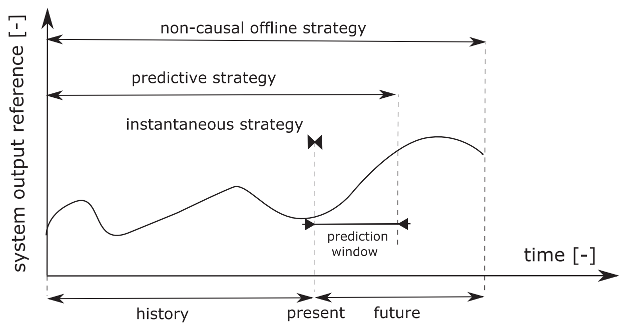

Figure 3. Optimisation time domains.

5. Available power system design tools

There is a shortage of commercial simulation and design optimisation tools for hybrid power systems in the marine sector. The RAptures tool in den Hertog et al. (2009) was developed to calculate the fuel consumption, emissions and investment cost of the power system, which is specified by the user. The input data for the model include vessel and component specific data, the duty cycle of the vessel and the topology of the machinery. However, power management optimisation capabilities between parallel power sources were not reported.

A system engineering framework for marine energy systems called DNV COSSMOS was reported in Dimopoulos et al. (2014). The modelling, simulation and optimisation software, developed by Det Norske Veritas (DNV), allows users to design the vessel power system from a library of components and study the energy efficiency, emissions, reliability and cost of the system. The level of detail in the modelling can be chosen from a dynamic presentation of the system using partial differential equations to a simplified steady-state description for more high-level design purposes. Embedded optimisation features and the capability of using

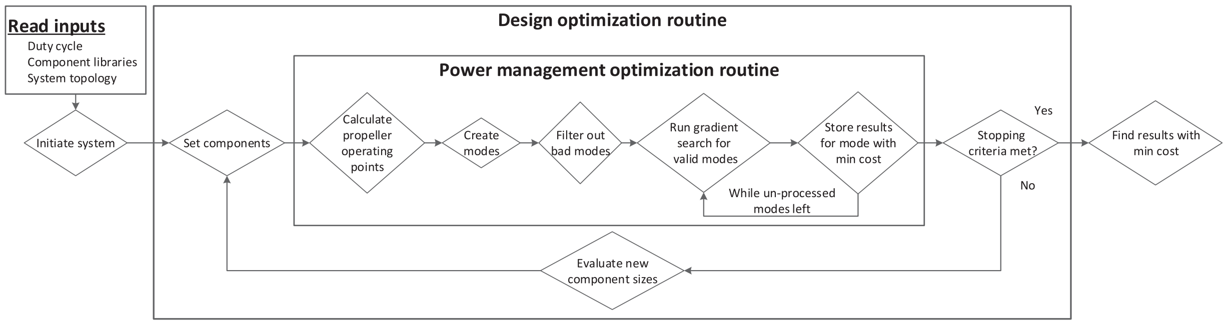

Figure 4. Block diagram for author's own optimisation methodology.

external optimisation routines are mentioned, but are not reported in detail.

HOMER Pro, in Unknown (2016), is a microgrid design tool which is suitable for various sectors in energy production. Although it seems to be mainly aimed for designing onland powergrids, it could well be used also in marine sector. It has a library with diverse range of component types for the user to compile and simulate the microgrid. It optimises the microgrid energy production using a 'modified grid search' algorithm and allows the user to make a sensitivity analysis, for instance, for different fuel prices. The algorithm itself is not described in detail as it is one of the main assets of the software.

6. Future work

The future target of the authors is to develop a tool for a vessel system integrator. Focus is on assisting in the decisions of power system design as early as possible during the design process. To keep the tool generic for different system topologies, the components and system configuration need to be easy to build and easy to modify for the sake of comparing different system alternatives. First, user specifies the components and vessel data in the library of the tool. For example, diesel engines, gensets, batteries, gearboxes and propellers can be specified. Using quasi-static component models, less parameters are needed and the data needed to specify them is easier to access through sales brochures or manufacturer measurement data. Also, a quasi-static duty cycle is specified by defining either the propeller load or with a combination of vessel resistance and velocity. Similar to propulsion duty cycle, user also specifies the hotel and auxiliary load in the electric grid. Then user specifies which components are chosen for the case study and how they are connected to each other and which modes they can operate. The load-sharing between multiple power sources is optimised in a global scheme by investigating the different modes the power system is capable of operating in. Optimisation algorithms, such as gradient based local algorithm, PSO and DP are already available for the user to choose from.

As a short preview, Figure 4 shows a block diagram of the optimisation procedure. Essentially, the core of the tool will be split in two layers: the design layer and the power management layer. The latter is an internal layer which finds the optimum usage for the machinery specified in the higher design layer. The design optimisation layer makes the decisions for sizing the machinery for a chosen topology. The power management layer will be presented next in the pipeline of future publications. The chosen propeller type (fixed/controllable pitch) and how it affects power management, is also brought in the frame of the design optimisation. For the future work, the main findings in this literature review were the nested structure of the design optimisation procedure from Silvas (2015) and the mode-wise local optimisation with electric motor as seen in Grimmelius et al. (2011). The approach used in the latter article can be used in conjunction with creating combinatory control modes seen in Linjama and Vilenius (2005).

7. Conclusions

This literature review presented an outlook on design and power management optimisation studies for hybrid power systems in marine vessels. The feasibility of using a hybrid power system in marine vessels is strongly affected by the duty cycle of the vessel. Numerical optimisation can be a useful tool to assess the feasibility of hybrid power system. This requires that the system integration designer knows enough about the whole power system behaviour and not just small sectors of marine technology. Although a vessel might show potential in cost savings using an energy-efficient system design and power management, the tight safety and reliability regulations coupled with more conservative mindset in the marine sector tend to set harder constraints in system design compared with the automotive industry.

The problem complexity and the required computational effort depend on the choice of the problem frame size, the method used to the search for the solution and the level of detail and dynamics of the system model. Whereas the power management problems for simplified convex systems can be solved on a laptop within seconds, the topology and sizing optimisation problem of a non-linear and discontinuous system may take days to solve even with parallel computing.

The authors of this article are developing a design tool for optimising marine vessel power system integration. More detailed description of this tool will be published in future and the next article will focus on the methodology for power management optimisation in this tool.

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