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# Towards Safer, Smarter and Greener Ships Using Hybrid Marine Power Plants

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## Introduction

This chapter gives an overview of research activities carried out at NTNU AMOS in relation to hybrid marine power plants enabling safer, smarter and greener ships. Recently electrical power plants with a set of diesel-generator sets segregated on several power buses have become the preferred solution for ships with a variation in operational profile and corresponding power demands. Examples of such ships are dynamically positioned (DP) vessels with electric power plants in the range of 10-80 MW used in the offshore oil and gas industry for various service, drilling, intervention and production operations, see Figure 1. The operations are characterised as safety-critical and will take place all-year with large variations in the environmental loads acting on the ship due to wind, waves, ocean currents, and recently more operations in sea-ice. Electrical power plants have also become the preferred solution for cruise ships, ferries, navy ships, LNG tankers, and icebreakers. The electric energy production may be powered by a hybrid marine power plant constituting of diesel engines, gas engines, and integrated with energy storage devices (ESD) such as banks of batteries. By proper design and control systems significant fuel savings can be achieved making the ships greener and safer.

Figure 1. Hybrid electrical power plants and advanced control systems enable safer, smarter and greener solutions for maritime transportation, offshore oil and gas exploration and exploitation, fisheries and aquaculture, offshore renewable energy, and marine science. Illustration by NTNU AMOS/Stenberg.

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The power and energy management system controlling the electrical power distribution, start and stop of generators, and the loads for propulsion, crane, drilling, ventilation, etc., is crucial in order to ensure safe and efficient operations. Successful operations of electrically powered vessels depend on advanced integrated software control functionality. Consequently, non-proper power plant designs and software-related problems, often in conjunction with hardware and/or human errors, may lead to unacceptable risk, increased gas emissions to the environment, and unwanted downtime during the operation. The associated loss of revenue and increased cost for the clients can be severe. Improved methods for testing and verification of hardware and software are important using improved simulation technology as well as laboratory testing.

The trend in the maritime industry is towards increased level of autonomy. This will put even more requirements on relevant and effective testing methodology in a lifecycle perspective. It is likely that new sky-based remote test services, monitoring and diagnosis of aboard systems, and logistics handling using digital representations combined with physical data from operations of the ship owner's assets, so-called digital twins, enable far more efficient software upgrading, including hardware/software-in-the-loop testing, without taking the ship out of service more than strictly needed. Remote monitoring and control from land-based operational centres with the ability to online access the fleet of ships, will also increase safety as well as the operational efficiency.

In this chapter, we will give a brief overview and summary of some research challenges and activities related to safer, smarter and greener ships addressed by the Norwegian Centre for Excellence NTNU AMOS in collaboration with research and industry partners. In particular, we will highlight the potential of introducing hybrid marine power plants with the benefit of using ESDs to reduce fuel consumption and gas emissions as well as to increase safety. First, the hybrid marine power plant will be described. Then, the most used energy management strategies for ESDs will be presented. Third, one control example using model predictive control (MPC) is shown. Finally, principles for testing and verification using simulator and power lab are briefly presented.

## Hybrid Marine Power Plant

A Recent development in the rules and regulations, i.e. class societies such as the DNV GL enables the usage of energy storage devices as alternatives to back-up generators in a marine power plant. Traditionally, a marine power plant consists normally of several diesel-generator sets connected to an AC or DC distribution system (power bus), separated by bus-tie breakers. In a hybrid marine power plant (see Figure 2), the generators are assisted by the presence of ESDs such as batteries, super-capacitors, and fly wheels. We have in particular been investigating the potential to use batteries. ESD is a device that can charge up and store energy and deliver it on demand.

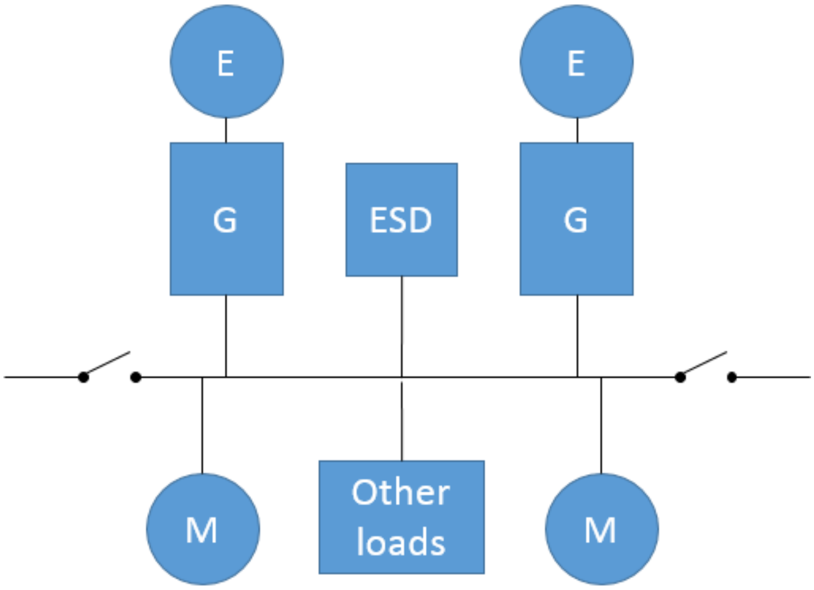


Figure 2. Simplified illustration of a hybrid marine power plant with two engine-generator sets and ESD supporting the energy consumer (motors and other loads).

As within the automotive industry, hybrid power plants on ships will improve safety and energy efficiency, since it can be used to reduce fuel consumption, emissions and power fluctuations. The propulsion motors are usually the largest power consumers on ships, depending on the environmental loads and modes of operation (transit, DP, etc.). In addition, there are usually several motors, frequency converters and transformers connected to the bus, which supplies energy to every electrical system in the vessel, such as hotel loads, drilling equipment, etc. In AC systems, the line frequency on the power bus should be fixed to either 50Hz or 60Hz, the same frequency of landlines, thus, forcing the generators to operate at fixed frequency.

Redundancy and segregation is used to increase the overall safety by having more generators, buses, thrusters, and associated electrical equipment connected than what is strictly required by the total load, as well as physically and electrically segregating the equipment and cabling into different branches and zones of the ship. Any single fault on the redundant system should not lead to blackout, that is, a total loss of power. A contradiction may occur while optimizing both safety and fuel consumption. Improved safety has up to recently resulted into requirements for operating the power plant with open bus tie-breakers with a hot standby engine-generator set on a neighboring power bus. Alternatively, fast load reduction or load shedding between the bower buses and enabled thrusters are chosen. Unfortunately, this safety-motivated minimum redundancy requirement far too often leads to operating conditions for the engine outside the optimal operating point, increasing fuel consumption and thereby the gas emissions. The introduction of improved generator protection systems, ESDs and smarter control systems may change this into a far better operation condition for the power plant and enabled engines. Even though marine operations and shipping are the most efficient transportation in terms of tons of goods per energy equivalent, the potential to improve fuel efficiency and reduce emissions are significant. We will in the following show some few examples of achievements to be obtained securing safer and greener by being smarter.

## Energy Management Strategies for Energy Storage Devices

Due to the increasing drive to reduce gas emissions and improve the overall power plant efficiency, alternative technologies are emerging as viable solutions for the future of marine technology. One particularly promising alternative to reduce fuel consumption is to use the newest ESD technologies, which allow the hybrid power plant to strategically load the generator, according to a reference model. ESD technology in terms of energy density and power capacity and functionality has improved its capabilities during the last decade. New class regulations, i.e. DNV GL (2015) open up for the ESD to be used as a spinning reserve. Then ESD has to be able to provide the necessary power to the power plant for at least 30 minutes in case of any single fault. The most common ESD usage strategies are:

- *Enhanced dynamic performance*: It is known that generator loading should be gradually ramped up. A too large or fast load increase might lead to a blackout. The ESD can supply energy to the power plant during large load steps, and the generator will be loaded gradually. This will improve the safety and robustness. Also, operations where large loads are expected, such as drilling, the vessels can operate with a smaller back-up power supply, due do the fact that the ESD will compensate for the abrupt power surge.
- *Peak-shaving*: The generator-set power supply should be bounded between a lower and a higher limit, and the generator-set load variation should not exceed a pre-defined magnitude. This operation is important in cases where engines might automatically start and stop, such as during Dynamic Positioning, DP2 and DP3 operations, leading to reduced efficiency in case of excessive engines running. Peak-shaving leads to reduction in fuel consumption and emissions and improve safety.
- *Spinning reserve*: Recent development in class rules and governmental regulations accept that an ESD, with certain requirements, can act as a spinning reserve. Hence, for redundancy purposes, less generators need to be connected to the bus at any point on time. This can be used to move the load per generator towards the optimal working condition, and, thus reducing the fuel consumption and emissions.
- *Strategic loading*: By charging and discharging the ESD, it is possible to strategically load the generator. Through high/low engine load cycles, it is possible to lower the average fuel consumption and emissions, compared to a system without the strategic loading. The viability of strategic loading is directly related to the engine fuel consumption curve characteristics and its curvature. Strategic loading viability requires a study for each individual vessel.
- *Zero emissions operation:* By shutting down the generators and using ESD only, it is possible to operate without any emission. A large ESD is required to supply the power demand from the vessel. This operation is interesting and may in the future become a requirement to operate the ships in port and harbours. It is also the sole operational mode on fully electric vessels.

## Direct Current Grid

During the last decade, DC grids have become an important alternative to AC grids for marine vessels. One of the reasons is the ability to run diesel-generator set with variable frequency. This makes it possible to increase the efficiency of the diesel engines by decreasing the engine speed at part loads, as the friction losses decreases. However, the rotational mass of the generator set can be used as an energy storage by varying the engine speed. This is especially useful in the event of a sudden trip of a generator set. In general, the engine speed should be as low as possible to increase the efficiency of the diesel engines. However, the speed may be increased such that the rotational mass can be used as an emergency energy storage in case of sudden trip of a generator set. The suggested model predictive controller (MPC), see Figure 3, automatically sets the optimal speed of the diesel engine, such that sufficient energy storage is available in the case of sudden disconnection of a generator set. MPC is suited for this task as it includes a model of the system. The MPC optimize the speed based on cost such as fuel consumption, torque variations, and speed variations. It also makes it possible to include the safety constraint (i.e. minimum frequency after a sudden disconnection of a generator).

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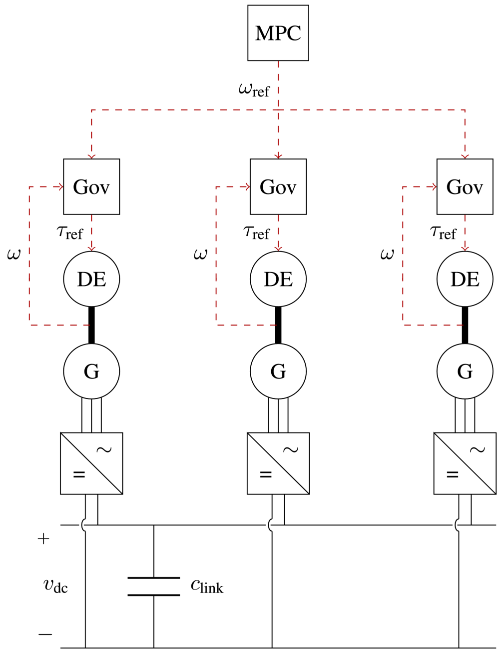


Figure 3. Block diagram of Model Predictive Controller (MPC).

## Power Smoothing

The use of batteries for energy storage is increasing for marine power plants. These batteries may be tens of kWh used for short term storage to multiple MWh used as primary energy source for a voyage. One of the use cases for smaller batteries is power smoothing. The batteries will then take care of the load variations, while diesel engines take the main load. However, heat will be produced in the batteries if they are used extensively. The aging of batteries is accelerated when the batteries are hot and the batteries may need to disconnect in cases where they are too warm. We therefore suggest removing the most challenging load fluctuations when the load fluctuations are large, while a broader spectrum of load fluctuations are removed when the fluctuations are small. This makes sure that we remove as much load fluctuations as possible, without overheating the batteries. This is done by using a statistical model to predict the expected heat generation in the batteries in combination with model predictive control to optimize the power smoothing. The model predictive controller (MPC) gives a configuration of the power smoothing controller which controls the power smoothing done by the battery, see Figure 4. MPC is a chosen, as this controller can include the statistical model to optimize the configuration. This means that the MPC can predict how different configuration will affect the temperature of the battery and therefore be proactive instead of reactive.

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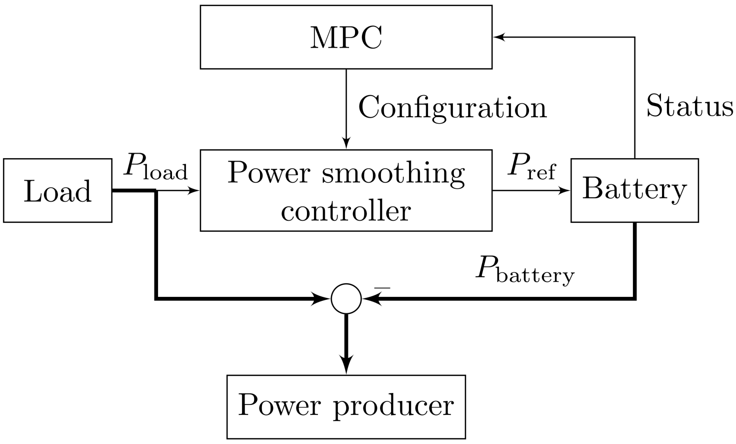


Figure 4. MPC configuration of the band-pass filter which control the power smoothing done by the battery.

## Design, Testing and Verification Using Simulator and Laboratory

System simulators are needed to investigate the performance of the entire system. The Marine Vessel and Power Plant System Simulator is a system simulator which includes the hydrodynamics, power systems, and control systems. The simulator models a marine vessel and is targeted for simulations of DP system and how it interacts with the power plant, see Figure 5.

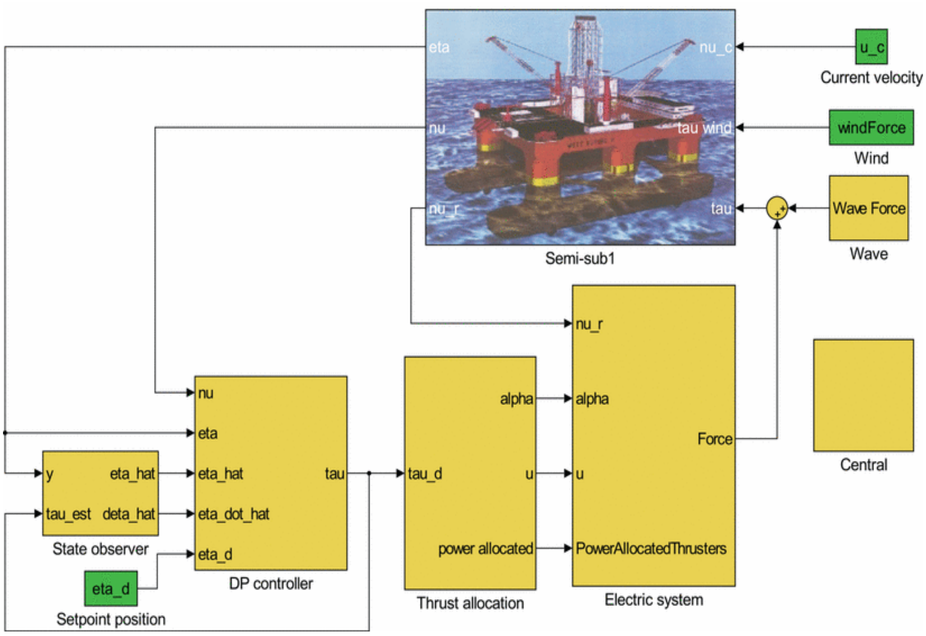


Figure 5. Marine power plant simulator with DP system.

Figure 5 shows that a DP vessel is modelled with environmental loads (ocean current, wind, and waves), a hydrodynamic model of the vessel, a state observer, a DP controller, thrust allocation, and the electric power plant.

The model is also suited for simulation of fault events, such as a sudden disconnection of a generator set. A fault recovery method is modelled such that the load demand is decreased of the power plant

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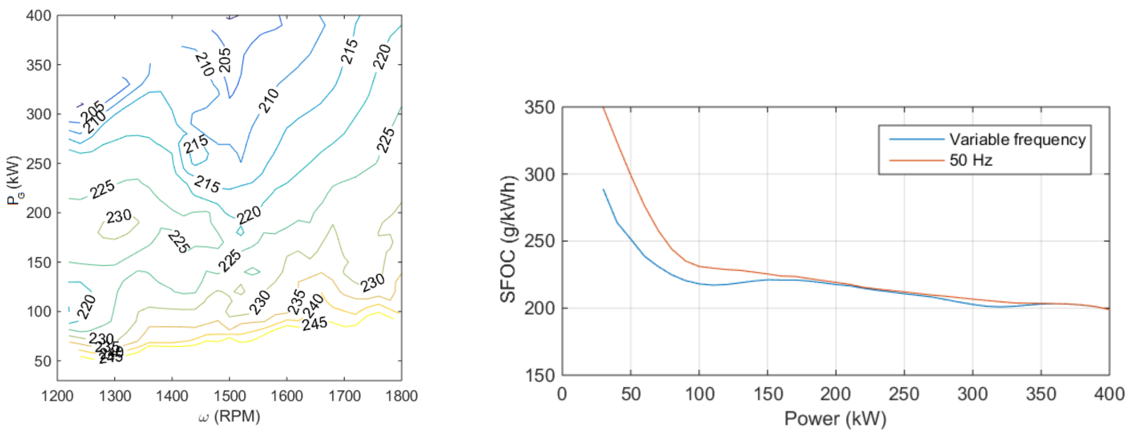
to avoid under frequency. This is possible by reducing the power of the vessel's thrusters. Therefore, the vessel will start to drift off. This is an example of a case where a system simulator is needed to be able to capture interaction effects between multiple subsystems of a marine vessel.

Currently, the simulator has been used to establish decision support systems for configuration of marine power plants based on fault event simulations. It is also used to simulate realistic electric load demand for establishing battery control systems.

Figure 6. Hybrid Marine Power at NTNU.

The hybrid marine power lab is a joint simulator by NTNU, ABB, and SINTEF Ocean. The lab consists of two generator-sets and two induction motors with torque brakes, see Figure 6. The diesel engines (200 kW and 400 kW) and generators can run at variable speed, which gives the opportunity to reduce the fuel consumption by running the generator-set at optimal speed, see Figure 7. The generators are connected to a DC grid through thyristor-based rectifiers. The induction motors are powered by two inverters connected to the DC grid. In addition, a battery pack of 45 kWh and a supercapacitor bank are connected to the DC grid through DC/DC converters.




(a) (b)

Figure 7. Hybrid marine power lab 400kW diesel engine specific fuel oil consumption (in g/kWh) as a function of the output power $P_G$. In (a) the mapping is shown as a function of the engine speed $\omega$, while (b) shows the SFOC for the case with optimum speed compared to fixed speed at 1500RPM.

This line-up gives the ability to test new control approaches suitable for DC grids. The diesel engine represents the slow dynamics of a marine power plant, and we are therefore able to investigate how this is affected by load variations and how it interacts with, e.g., the propulsion system.

## Furter Readings

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