2019 - OPTIMIZING THE PERFORMANCE OF A DIESEL GENERATOR-BATTERY HYBRID POWER PLANT WITH ENERGY MANAGEMENT INCLUDING A FLYWHEEL

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ABSTRACT

In a continuously developing marine electrical world, the demands on fuel consumption and greenhouse gases reduction are becoming stricter. More vessels are exploring the options in using alternative energy sources – batteries, flywheels etc. – to improve their operation. For systems with more than one energy source, an energy management system (EMS) becomes a vital component. In addition marine power sources are dynamic by definition and require additional precautions to be controlled. The task of an EMS is to optimize the operation based on a specific goal or goals, having as a primary goal the minimisation of fuel consumption, and as a result the exhaust pollution reduction. Implementing an EMS in a hybrid ferry, including diesel generators and batteries has led to a considerable reduction of fuel consumption, of even up to 38%.
A further objective of the EMS is to optimize the total cost of ownership (TCO), i.e. the lifetime, wear and tear, and maintenance requirements of the complete power plant equipment. As a first step the battery lifetime is incorporated in the controller. This is realised by carefully observing battery lifetime determining quantities, like state of charge (SOC) and magnitude of charging- and discharging currents. The latter can be additionally improved by the application of a flywheel which leads to a better grid stability, taking up high powers, which is a limiting factor for the batteries. Unlike the batteries, a flywheel is a long-lasting device that can offer many years of reliable performance and implementation in combination with batteries, can lead to an even more long-lasting battery lifetime.
The paper describes how the above has been integrated into the EMS and demonstrates the fuel consumption reduction operational results. In addition showing simulation results of how controlling the battery usage maximizes the battery lifetime and how the application of a flywheel further improves the performance of a diesel generator-battery hybrid power plant.

Keywords: Energy Management; Hybrid Propulsion; Optimisation; Battery Lifetime; flywheel

1. Introduction

Design stage power and energy requirements are dependent on the intended vessel mission profile. On the basis of achieving optimal power system operation on board of a ship, generating the required power in the most efficient point can be considered the foundation of the most optimal way of operation.
In shipping industry the power generation plant is usually managed by the operator in combination with a Power Management System (PMS). Introducing a variety of choices by means of a hybrid power and propulsion plant increases the level of operational control, especially if the operator continuously wants to manage this in light of a global optimum.
This can automatically be achieved by means of the Lagrange algorithm which decides the power generation set-points of the sources for a given operational profile. The optimization algorithm deciding upon the energy generation allocation is called Energy Management System.
The main task of the EMS is to optimize the operation based on specific goals mainly focusing on the minimization of fuel consumption. However, in order to achieve a global optimal performance on board of a ship many more factors should be taken into account. Optimizing the fuel consumption is a goal which could lead in decisions against the optimal operation of other equipment. In order to optimise the total performance of a ship, one should not neglect the operation and maintenance of on board assets.
A battery energy storage system, for example, is considered as a relatively cheap source of energy on hybrid systems because it can be a mean to realize fuel saving. However, such a system is a costly investment, so the maximization of the battery lifetime should also be considered. There is a trade-off between the battery lifetime maximization and fuel consumption minimization; thus both should be taken into account when striving for maximal cost efficiency. As a first step towards optimising TCO, this paper presents an EMS

which minimizes fuel consumption by taking into account the battery lifetime for a load profile of a ferry. As an additional step the integration of a battery lifetime model in the existing algorithm was performed for a hybrid super yacht load profile, as well as the impact of implementing a flywheel to a hybrid power plant, for the load profile of a cutter suction dredger.

An EMS with battery lifetime incorporated was developed and tested using simulations. Simulations performed including the battery lifetime in the EMS are shown and gave new insights in the performance and limitations of energy management systems in general. In addition operational saving results and battery usage for a ferry are presented and finally integration of a flywheel on a cutter suction dredger load profile which provides indispensable knowledge for the development of future hybrid power plants.

2. Optimization algorithm

Whereas in most current energy management systems the only aim is to save fuel costs, this optimization algorithm considers the battery lifetime as an important goal. In order to do this, both the fuel consumption and the battery lifetime are used in the optimisation algorithm.

In order to optimise the fuel consumption, the Equivalent Consumption Minimisation System (ECMS) is used. This method has proven to be suitable for application with any load profile (Berecibar, et al., 2016). When using the ECMS second order cost functions are defined for every generating unit for which the cheapest solution is found using Lagrange relaxation.

A practical implementation of the above can be divided in the control algorithm and the placement of the vessels control system. The following figure depicts the control loop architecture with the resulting control interface signals.

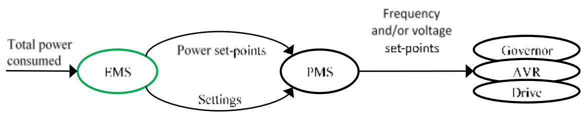

Figure 1: EMS Control loop architecture

The cost functions for the diesel generators can be found by fitting a second order polynomial on the fuel consumption curve; thus, cost functions of the following general form can be found.

$$F = aP^2 + bP + c$$

The fuel costs for charging the batteries, corrected with estimated battery losses, should also be expressed in an equation of a similar form. As published earlier in (Breijs & Al Amam, 2016), this can be done using the following equations:

$$a = \frac{\left(\frac{1}{\eta} - 1\right)}{P_{nom}} \times SFC_{batt}(t)$$

$$b = SFC_{batt}(t)$$

$$c = 0$$

$$SFC_{batt}(t) = \frac{SFC_{batt}(t-1) \times SOC + \overline{SFC_p} \times \Delta SOC}{SOC + \Delta SOC}$$

$$\overline{SFC_p} = \frac{\Delta(\mathrm{SFC}_{\mathrm{DG1}} \times \frac{P_{DG1}}{P_{plant}} + \mathrm{SFC}_{\mathrm{DG2}} \times \frac{P_{DG2}}{P_{plant}} + \mathrm{SFC}_{\mathrm{DG3}} \times \frac{P_{DG3}}{P_{plant}})}{\Delta t}$$

Whereby η equals battery charge and discharge efficiency and P_{nom} the nominal battery power. SOC represents the percentage of stored capacity and ΔSOC the state of charge increase, while the SFC is the specific fuel consumption per generator. The cost of charging energy for the batteries is dependent on the operating conditions of the vessel. In some cases the batteries are considered to be only charged by the DGs, as defined in Equation (6), and in other cases considered charged also or only by the shore.

3. Battery fuel cost price

The aim in adapting the battery fuel cost price is to incorporate factors which would lead to a longer battery lifetime and as a result minimizing the total cost of ownership. The equations aiming the minimization of the fuel consumption required some modification, to include the battery lifetime. In order to achieve that, the factor b is modified in the battery cost function.

$$b(t) = b(t-1) \times \left(1 + b_{offset}\right)$$

$$b_{offset} = \text{Penalty Factor [-]}$$

The EMS architecture is shown below in Figure 2. The Lagrange multiplier method is used to optimize fuel economy, respecting the operational constraints of the generating units. As a result the Lagrange multipliers are adapted based upon the vessel's mission.

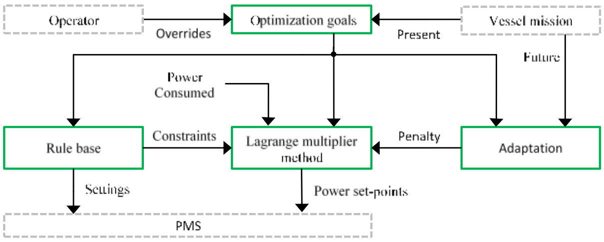

Figure 2: Energy Management System architecture

3.1 Battery cost price on a ferry case

For the battery cost function the Lagrange multiplier initially for the ferry load profile is adapted with a penalty factor including the number of daily cycles. This resulted in the desired daily cycles and on the desired battery operation. In the case of a ferry, operational results proved that adapting the battery fuel cost function, lead to the desired battery behaviour. As a result, the battery is used during the complete time schedule with the allowed number of cycles. The system of a ferry consists of three diesel generators and two battery energy storage systems connected to the propulsion drives, see Figure 3, and the load profile and the operational results for one normal day are shown in Figure 4.

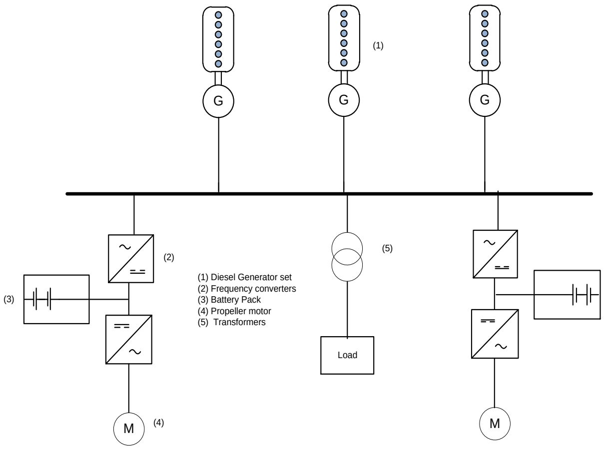

Figure 3: Hybrid ferry system

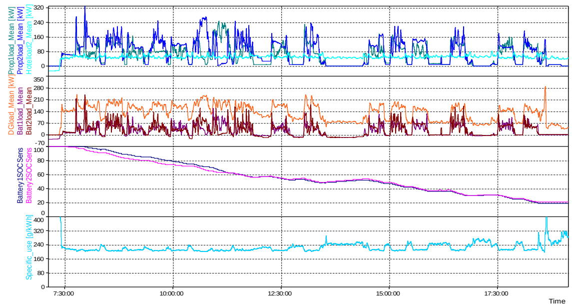

Figure 4: Operational results on a weekday on a ferry

3.2 Battery cost price on a super yacht case

In order to make a more accurate model, more factors that could impact the battery lifetime were taken into account. In this way we developed an active control of the lifetime set-point and implemented this in the EMS software. To simulate the performance of the modified EMS on an unpredictable operational profile, the case study of the hybrid super yacht has been used. Where many current hybrid vessels such as ferry's and tugs have a more or less repetitive and predictable load pattern, this is not the case for a super yacht. Optimising for unpredictable load patterns requires the EMS to provide the optimal solution for a wide range of load patterns.

The system model of a test case, such as a super yacht consists of three diesel generators and two battery energy storage systems, see Figure 5. A load profile is created, using real life data samples. In these data samples the time spent berthed is filtered out, resulting in an eleven day load profile shown in Figure 6.

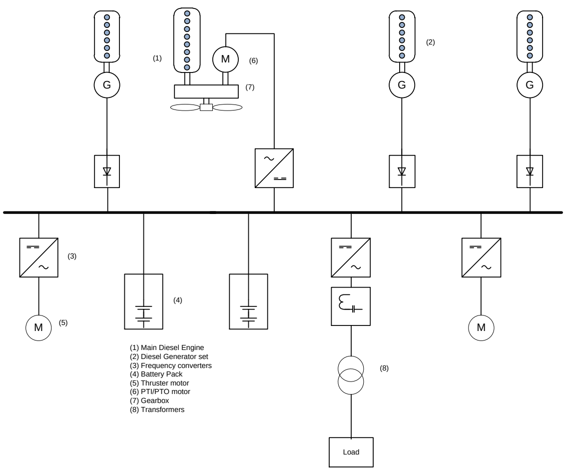

Figure 5: Hybrid super yacht system

The demand shown includes the propulsion load, hotel load and bow and stern thrusters. For the simulations, different multiple day extractions from this load profile have been used to analyse the system performance.

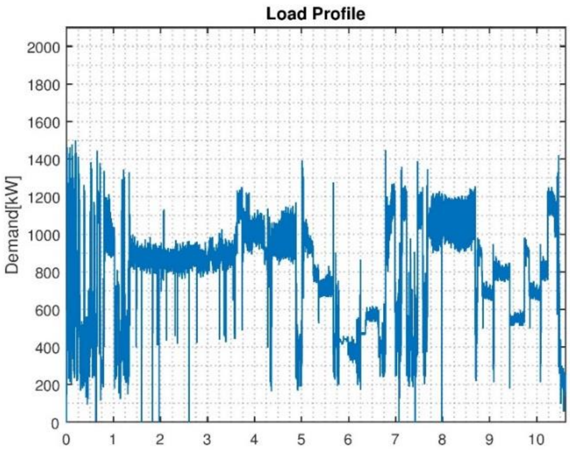

Figure 6: Load profile of the hybrid super yacht

It is worth to mention that for lithium-ion batteries, adaptive models with sufficient accuracy are not available. On the other hand there is plenty of research that has been done on experimental methods resulting in relatively accurate models, which provide sufficient accuracy for practical use. Therefore by using results of an experimental method values such as the charge and discharge rate and the number of charge discharge cycles are important to determine the remaining lifetime of the battery. The input for this method is the SOC which is relatively simple to measure.

The modified EMS as explained, is adapted with a variable cost function for the battery price. This variable cost function is created by defining the penalty factor as a function of the desired and predicted years. In the case of the predicted battery lifetime being greater than the desired lifetime, the battery cost function is reduced leading to a greater use of the battery. This results in a reduction in battery lifetime and reduction in fuel costs. If the battery lifetime is smaller than the desired lifetime the battery cost function is increased. This leads to a decrease in battery usage and therefore to increase in battery lifetime. The penalty gain can be used to make the system more or less sensitive for a deviation from the desired lifetime. There are several gain values tested and implemented in the battery cost price as it can be seen in Figure 7, where a penalty gain $K_p = 1$ and a set-point of 3.5 years is used. The graph shows that for each load profile the system is capable of reaching the desired battery lifetime.

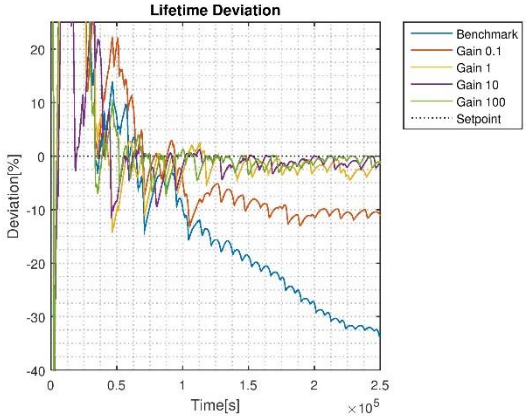

Figure 7: Set-point 3.5 years

4. Implementing a flywheel on a hybrid power plant

Introducing diesel generator-hybrid power plants on vessels with high power peaks such as cutter suction dredger or offshore vessels with (AHC) cranes, leads to additional challenges in optimizing the balance between operational cost and battery lifetime. In classic configurations additional engines are running to handle these high power peaks, these can be eliminated by introducing hybrid configurations. However the occurrence of high power peaks on diesel generator-hybrid power plants results in the battery acting as a peak shaving system. This operation typically sees the highest charging and discharging rates for the battery. These rates are battery lifetime determining quantities that lead to bigger batteries in the sizing stage (Berecibar, et al., 2016). A typical load profile with frequent high power peaks is the one of a cutter suction dredger as shown in in Figure 8.

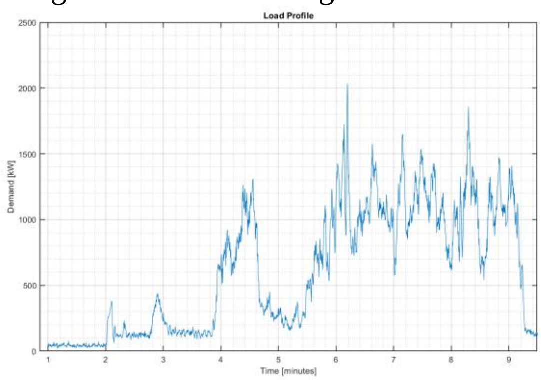

Figure 8: Load profile of a cutter suction dredger

The application of an Energy Storage System (ESS) tailored specifically to the peak-shaving functionality has the benefit of an optimized control of the charging- and discharging rate for batteries. The system model of a test case with such a load profile, such as a cutter consists of three diesel generators and two battery energy storage systems and a flywheel motor, see Figure 9.

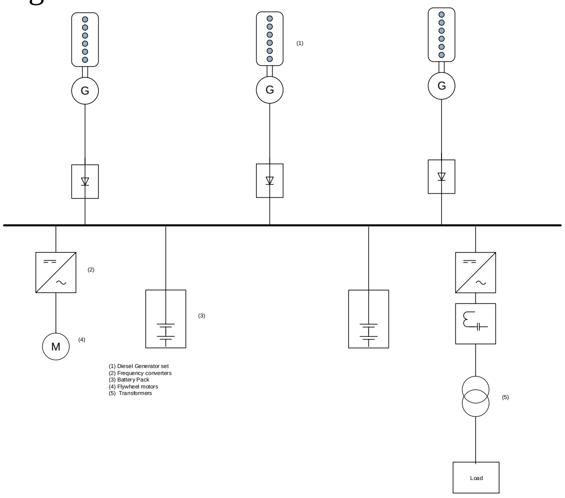

Figure 9: Hybrid cutter system with a flywheel

Flywheels have excellent peak-shaving qualities for mitigating power peaks taking place in very short time frames without being penalized in operational lifetime. Unlike the battery, the flywheel is not limited to charging cycles allowing for continuous charging- and discharging cycles. The flywheel is also a (thermally) robust apparatus allowing for placement in ambient conditions not suitable for batteries. The proposed flywheel addition to the diesel generator-hybrid as seen in Figure 9 consists of: A rotating mass, motor and inverter. The rotating mass and motor operate as spinning reserve sized to the maximum power peaks taking place.
The inverter controls the flow of power to and from the flywheel. Through fast and accurate measurement of the consumer loads and the set-points of the supply, the power deviation is calculated. The inverter controls the charging and discharging of the flywheel with power rates up to multiple hundred kilowatts per millisecond to make up for this difference in power. In a second control loop, the flywheel stored energy is controlled to an optimal set point allowing for maximum peak shaving depending on the operating condition. For the control architecture, see Figure 10. Depleted energy in the flywheel is replenished taking into account the charging rate of the battery, see Figure 11.

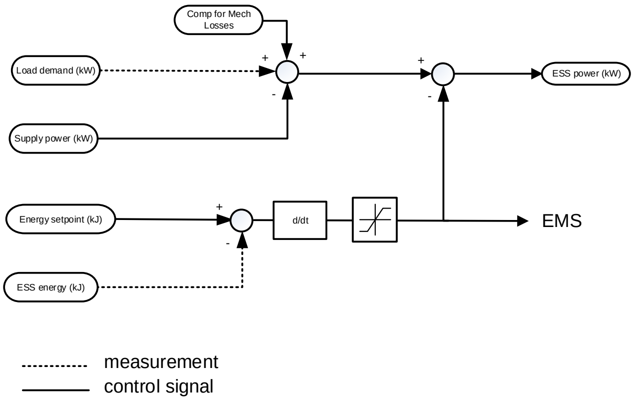

Figure 10: Flywheel control system architecture

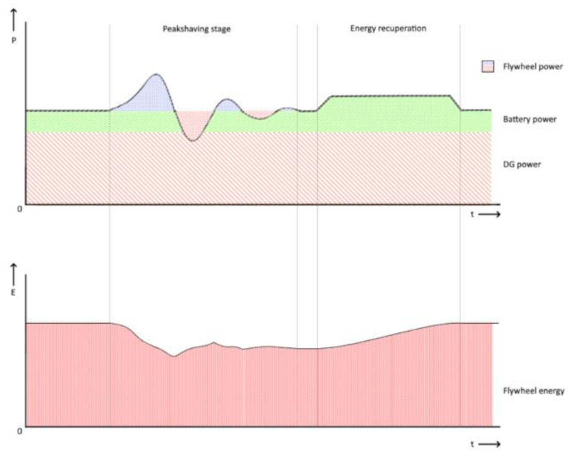

Figure 11: Flywheel behaviour on a hybrid cutter system

5. Conclusion

As a result, the influence of the control on the test case of a ferry is presented on the operational results in section 3.1. The result indicate that the cost price optimization method can be adaptive and influence the behaviour of the system towards the desired direction.
After validation of the system, the modified EMS for the test case of a hybrid super yacht is simulated using several samples of the load profile as shown previously. The results of these simulations are presented and discussed in section 3.2. The predicted lifetime at a moment t[s] is based on previously obtained information up to that given point in time. This explains the rather unstable behaviour in the beginning since at that time to little historical data was available for a reliable prediction.

Section 4 describes the impact and constraints of the introduction of a hybrid power plant on vessels with a load profile with high power peaks. It is shown that for those application additional measures are required to optimize the battery lifetime and operational cost. This due to the fact that those appear in that time domain which is not handled by the EMS part. It is apparent that the load profile significantly influences the lifetime and operational cost. Simulations on the cutter test case in introducing a flywheel into those systems have shown to be a way of optimizing the total system performance in terms of operational costs.

As a first step in the transition towards optimizing the TCO, the battery lifetime is incorporated in the EMS of a hybrid super yacht. A dynamic battery cost function is used to find the cheapest solution for any load demand. In the case of a ferry, adapting the cost function with coefficients in order to achieve the battery usage on the complete day was succeeded. In the case of a yacht based on a novel battery lifetime prediction method for Li-ion batteries, the battery lifetime was predicted and the battery cost function was influenced to reach the desired battery lifetime. This method was tested through simulations and resulted in the battery achieving its requested lifetime, without any major impact on the fuel consumption. In the case of a cutter suction dredger, the battery lifetime can have a major impact by providing these peaks with a flywheel. So after a study case on such a load profile, it is expected, that adding a flywheel would improve the grid stability and the power fluctuations on the battery for these type of vessels, while maintaining the lifetime and the installed capacity.

This paper has also identified new challenges such as including the SOC and the number of start stop cycles in the optimisation process. It is questionable it can be properly achieved for each generating unit. Research for alternative algorithms for optimising the TCO and implementing multiple goals in a shorter time domain is recommended.

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