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Investigation of Diesel Hybrid systems for fuel oil reduction in slow speed ocean going ships

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ABSTRACT

The volatile world economy and the adoption of stricter emission policies from the European Union and the International Maritime Organisation greatly affect the shipping industry. This paper is focused on the potential of Diesel Hybrid power systems to increase fuel efficiency for ocean going slow speed ships. Alternatives in on-board energy generation, management and storage strategies are investigated. The mathematical implementation and simulation of the power train components is demonstrated using a systematic approach. Vessel operational profiles were incorporated to the power train optimisation problem. The optimisation scenarios were run using a modified marine power systems version of the Equivalent Cost Minimisation Strategy. The results indicate fuel savings for auxiliary loads as a result of the absence of conversion losses. For the main Diesel hybrid propulsion, the system is deemed infeasible. Nevertheless, for the combined Hybrid power train, the savings are achieved by proper handling of the originated energy from the Main and Auxiliary engines.

1. Introduction

The world shipping is forced to comply with strict emission policies while it faces the worst economic recession. Consequently, shipping has to minimise the fuel consumption in order to adapt to the present status, although the emission projection is reduced from 2.7 to 2.2%. The IMO [1] notes that in 2007 approximately 277 million tonnes of fuel were consumed by international shipping. The dry bulk sector is considered as the third most pollutant sector accounting ~53 million tonnes fuel/year [1]. The significant portion is shared by Handymax and Panamax (up to 80.000 tonnes deadweight) bulk carrier sub-categories [2]. Both in terms of quantity and of global warming potential, other GHG emissions from ships are less important and current European framework projects aim in abatement technologies for Nitrogen Oxides and Sulphur oxides, with promising results [3]. These measures if implemented, could increase reduce the non-GHG emissions rate by 25%–75% below the current levels [4]. Many of these measures appear to be cost-effective, although financial barriers may discourage their implementation [1]. EU parliament voted in 2016 the mandatory monitoring of fuel consumption and CO2 emissions of ships calling or departing from EU ports. Methods to measure are yet to be finalised. Nonetheless, CO2 emissions will be eventually targeted by regulation bodies within the next couple of years and discussion on CO2 levy are ongoing.

Hybrid technology, which combines prime movers and energy storage, has been successfully implemented in vehicles in the automotive industry [5]. The latter application has been shown to contribute to reduced CO_2 emissions taking into account real drive cycle data [6]. Moreover, depending on the driving parameters, the charge output of the Hybrid Power system and the battery SOC greatly affects the CO2 emissions [7]. In land applications, various studies and installation appear in the industry. A recent and of large scale project is found in Algeria. The feasibility and sensitivity analysis of PV-hybrid diesel battery system showed good potential, and suggested an optimum power split between the power sources [8]. Investigation on PV/wind independent system recommending optimum sizing proposals and estimation of levelised unit electricity cost using iterative techniques and the deficiency of power supply probability (DPSP) model is made in Ref. [9]. In Ref. [10] it is concluded that the amount of excess energy from the off-grid hybrid arrays affects the cost of energy.

In shipping, recent studies have been made towards hybridisation. The majority of them utilise additional power harvested from renewables, hence, energy storage installation is imperative. Consequently, studies focusing in determining the optimality of

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electrical and storage components are published, as the latter play a significant role in the feasibility of the system. The optimal sizing of batteries using non-linear optimisation techniques is investigated in Ref. [11] while the overall process in similar land based systems in Ref. [12]. Other control strategies, mainly for load sharing optimisation, are presented in Ref. [13].

Nonetheless, the use of renewables in hybridisation of power system on ships is favourable but increases the complexity and introduces large uncertainty factor of solar radiation in financial feasibility studies. Various studies attempt to quantify and measure the effect of solar radiation [8], a method of irradiance estimation is presented in Ref. [14] while the complexity of PV array, the benefits and potential fuel reduction in ships is discussed in Ref. [15]. Further financial feasibility analysis hybrid ship operation is presented in Ref. [16].

This paper attemps to demonstrate a methodology to evaluate the hybrid solutions on different topologies and in different propulsion scenarios as ocean going vessel operations do not follow a regular pattern. Furthermore, it is focusing on utilising solely the power generated from the prime movers and not from renewable sources, thus it eliminates uncertainty parameters and avoids complex optimisation techniques such as particle swarm optimisation or genetic algorithms to account for the solar radiation vectors [11]. The implication of excess of energy discussed in Ref. [10] is not applicable in ship applications as vessels are designed with specific powering principles and the retrofit topology does not involve other power generation components. This approach reduces the CAPEX and removes the necessity of large areas on deck to accommodate solar panels or other renewable source equipment. Driven by same principles and due to the absence of free deck space [17] investigate the hybridisation of cranes on board bulk carriers using the existing machinery, underlying that ships with fluctuating loads benefit the most. Additional commercial studies are on-going by a well-known ship crane company, in order to regenerate power during hoisting movement of cranes, reduce the magnetic breaking effort and meanwhile harvest the lost energy returning it to the ship's grid.

The local emission problem in ports, inspired other studies to focus on the hybridisation of tug boats [18], with promising results. Finally the most complete study in the domain occurred by Ref. [19] on an offshore supply vessel. The full-scale experiment used lithium ion batteries and all-electric concept demonstrated main savings due to power management concept which the hybrid system offers. Due to the increased potential of Hybrid solutions, DNV-GL has published the first rule set for battery existence on-board in an attempt to early impose regulations and extra safety to ships. Currently in the classification portfolio more than 8 ships will have battery installed power, the majority of them supply vessels.

Although there is no capability of regenerative braking in ship propulsion loads, the Hybrid implementation on vehicles permitted to identify means of improving the energy production of the prime movers and at the same time try to estimate future demand, so always maintain the most fuel efficient energy production. In order to assess the marginal implementation of the concept, the investigation is focused on slow speed ships, which are considered to be less favourable on Hybrid solutions [20]. The investigated system was statistically validated in Ref. [21] using static efficiency factors and this system proved to have negligible effect on deadweight [22]. The points that this paper develops are whether the hybrid concept is feasible when using the actual efficiency curves of power components. Secondly to demonstrate an optimisation/decision tool to assess in every load case on how a potential Hybrid ship should operate. Thirdly to present the optimum power split of energy production on each propulsion scenario and finally answer if the optimum energy management is capable of maximising fuel efficiency without the existence of energy storage media. To date, a holistic study of hybridisation of existing power topologies for both propulsion and auxiliary loads was not attempted before.

2. Hybrid system concept

Ships depending on their operational profile and purpose are equipped with propulsion and auxiliary engines. Especially for the bulk carriers the prevailing designed topology is one direct propulsion slow speed engine and three auxiliary generator sets which cover the navigational, hotel, auxiliary and cargo related loads if any. The number of auxiliary engines is determined by the classification societies accounting redundancy purposes. Each generator can run independently on manual mode or automatically using the load sharing option paired with a second generator.

Marine Diesel Engines are optimised for a broad range of operation. The amount of energy for given RPM is determined by the environmental conditions and the hull and propeller fouling. Nevertheless, the increased bunker cost has led the engine manufacturers and researchers to adapt the engine fuel efficiency for low or part load operation for propulsion engines, penalising high loads, which are usually met at high speeds or high seas. The slow steaming operation of non-eco ships results in engine operation at non fuel-efficient points [23]. Moreover, the recent trend in shipbuilding to meet low Energy Efficiency Design Index (EEDI) points may lead to questionable sizing of propulsion engines and underpowered vessels.

For auxiliary generator sets, although their operation is at constant RPM to maintain electric frequency, they are capable of serving loads ranging from 10% up to 90% of the maximum power. In cases that high power load is demanded, the load sharing option is enabled. However, this greatly narrows the energy efficiency as in many cases is done in order to avoid temporary load increase, reactive power issues, problems on electric quality that can lead to sudden ship black-out etc.

Fig. 1 depicts the optimisation concept for propulsion loads. For this example, it can be assumed that the engine is optimised to serve 5000 kW at 104RPM with the minimum Specific Fuel Oil Consumption (SFOC). The sea state is increased; therefore the engine has to adapt the rotational speed so the propeller can produce the required thrust, consequently the load is also increased by 900 kW. The total fuel bill is the multiplication of SFOC and the total kW. For propulsion scenario, equations (1) and (2) explain the optimisation algorithm principle.

$$SFOC_{primemov} \cdot P_{primemov} + SFOC_{hybrid} \cdot P_{hybrid} \leq SFOC'_{primemov} \cdot P'_{primemov} \quad (1)$$

The following constraint applies for the power split:

$$P'_{primemov} = P_{primemov} + P_{hybrid} \quad (2)$$

The SFOC is load dependent, thus, if the engine operates at a less efficient point, the total amount of kW is produced inefficiently. Using the Hybrid system, the prime mover produces only the power with the best fuel efficiency. The rest is covered by the Hybrid module even though the fuel efficiency of this portion is significantly lower. Thus, although more energy is produced and portion of this is produced with low efficiency, the total fuel bill is less, leading to absolute fuel savings [tonnes/day].

This Hybrid power system is denoted as Series-Parallel Hybrid because the Diesel engine should primarily be capable of supplying energy to the propulsion, as the latter system requires tens of MW in large bulkers and secondly in order to avoid an extreme amount of stored energy on board, something that jeopardises the technical