BESS-Based Hybrid Propulsion: an Application to a Front Line Naval Vessel Preliminary Design

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Abstract. The paper conceives a flexible new generation naval ship Destroyer (DDX, Destroyer, Experimental) with a primary focus on low environmental footprint, high efficiency, and reliability. The ship implements an innovative propulsion power generation and storage system based on a CODOGOL (COmbined Diesel Or Gas Or eLectric) architecture and a Battery Energy Storage System (BESS). The proposed modular solution is also suitable for retrofitting applications and represents an innovation in the state of the art of hybrid propulsion systems for big, front-line naval ships. The shipboard BESS is used as a backup power source to ensure minimum generator operation (MGO) mode reliability requirements. The benefits of the proposed solution are discussed in detail, highlighting a reduction of the operating costs and fuel consumption, as well as low pollutant emissions and Life Cycle Costs. Eventually, dynamical simulation is used to assess the effectiveness of the proposed solution in critical conditions.

Keywords. Naval ship, DDX, Hybrid propulsion plant, Battery Energy Storage System, Backup power source

1. Introduction

The major Navies worldwide are going through the modernization of their fleets, especially regarding front-line ships. Operational flexibility, extended speed ranges during navigation, and reliability are challenging requirements. At the same time, the major Navies are shifting their attention to efficiency, operating costs, and environmental footprint of naval ships, but reducing the carbon footprint of a front line ship is a demanding task during design stages.

Hybrid and full-electric propulsion is in the spotlight of the current scientific literature. As an example, [1] discussed a comprehensive review of the existing propulsion plant layouts for naval ships, while [2] presented an overview of the promising technolo-

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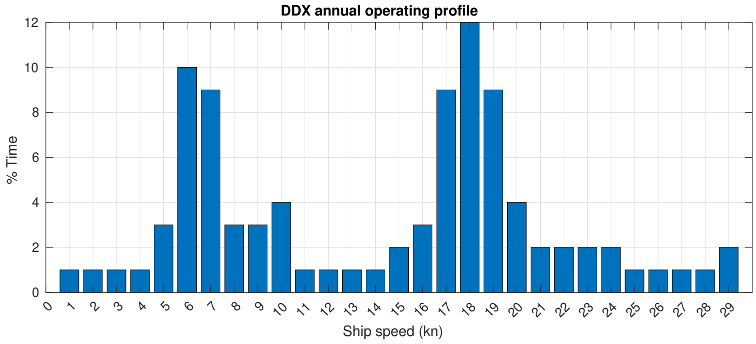


Figure 1. A typical operating profile of a new generation Destroyer with the stated mission requirements

gies in marine electric propulsion. An interesting insight on the electrification trend occurring on warships was given by [3], at the same time providing a clear glimpse into the future of shipboard power and propulsion systems. [4] presented an optimization-based approach to the preliminary sizing of prime movers on a ship in a hybrid propulsion framework with DC distribution. [5] presented a refitting of the propulsion system of a research vessel, implementing a hybrid propulsion plant with BESS (*Battery Energy Storage System*). [6] analyzed different technical aspects of integrating BESS into a shipboard full-electric plant regarding a 4000 t naval ship.

This paper proposes a novel hybrid propulsion plant architecture application with a BESS on a new generation Destroyer ship. The paper aims to assess the benefits of introducing hybrid propulsion technology on such a naval unit to accomplish specific mission requirements, paying close attention to the reliability of the electric power supply in MGO (Minimum Generator Operation) mode. During emergency conditions and in MGO mode, the Battery Energy Storage System integration provides the necessary reliability levels required by the electric power supply for military purposes. The preliminary design of a new generation Destroyer of over 9000 t is considered a case study to assess the potential benefits of the proposed solution. The ship design is performed considering an appropriate operating profile; furthermore, fuel consumption and CO_2 emissions are estimated and compared with a traditional propulsion plant with the same layout and requirements to assess the potential benefits of the proposed solution. In conclusion, realistic operational conditions challenging the system reliability are simulated to demonstrate the effectiveness of the proposed architecture for the propulsion plant.

2. Design process and methodologies

Traditionally, the design of a naval ship relies on an iterative process called "design spiral". The on-board integration of weapon and sensor systems is the main peculiarity of naval ship design and substantially differentiates it from merchant vessels [7]. The first step in the design process is analyzing the operating profile. Figure 1 presents a typical operating profile of a Destroyer.

According to Figure 1, the ship mainly operates at low and medium speeds. Therefore, optimizing low and medium speed ranges is a primary drive when conceiving the propulsion layout. However, the capability to reach the maximum speed is a mandatory requirement. Analyzing the fleet of nowadays operating naval ships, it is worth noticing that the unmatched flexibility required by the operating profile of a naval ship implies a rather complex propulsion system architecture. Propulsion systems often feature gas turbines to reach the maximum design speed and usually rely on Diesel or Diesel-electric propulsion to achieve high performance at cruising and patrolling speeds.

Hybrid propulsion systems provide reliability and operational efficiency while reducing fuel consumption, environmental footprint, and maintenance costs. In particular, a hybrid propulsion system allows high efficiency for a wide range of brake torque output of the propulsion machinery by running the minimum number of generators operating near their maximum achievable efficiency. Moreover, minimizing the use of thermal engines at light loads reduces the radiated noise. Eventually, hybrid architectures can potentially improve vessel survivability by targeting vulnerability and recoverability. Recoverability, in particular, is strictly related to the flexibility of the propulsion system and the amount of available operating modes, while the vulnerability is influenced by machinery segregation.

The flowchart in Figure 2 summarizes the design procedure of a propulsion plant type and layout for a front-line ship.

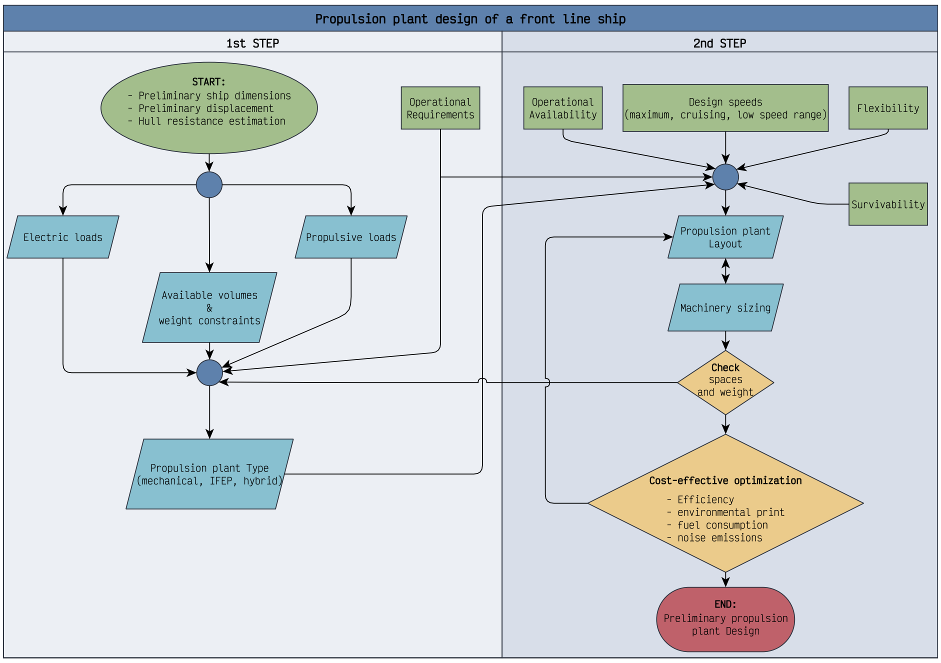


Figure 2. A flowchart summarizing the selection procedure of the propulsion plant for a front-line ship

3. The Role of Battery Energy Storage Systems

On-board of nowadays operating front-line ships it is a common practice to maintain one more running generator than necessary, to guarantee redundancy and immediate power backup. Consequently, the engines used for electric power generation operate at light load, with low efficiency, higher fuel consumption and increased running costs.

In this perspective, this paper proposes the adoption of a Battery Energy Storage System (BESS) as a temporary backup power source to maintain reliability requirements in MGO mode. The BESS is sized to guarantee a temporary backup for propulsion and service loads in emergency conditions if one generator fails: the personnel can then start-up an additional machine without the electric power supply being interrupted, and avoiding a black-out. According to the usual redundancy-based approach used in military applications and warship design, the BESS should be split into several Energy Storage Modules (ESMs) located into independent ship compartments to ensure enough redundancy of the power supply and improve the survivability of the ship.

4. Case study

The case study of this paper is a new generation Destroyer preliminary design. The mission and technical requirements analysis led to an overall length of 165 meters, a maximum breadth of 21.80 meters, and a molded depth of 12.60 meters. The full load displacement is estimated 9170 metric tons, with a full load draught of 5.86 meters.

The ship must guarantee the design maximum and cruising speeds with a Sea State of level 3 and a Wind State of level 4 on the Beaufort scale after 18 months outside the dry dock. The operating profile shown in Figure 1 requires steaming at low speed for a significant part of the vessel's lifetime. A CODOGOL hybrid propulsion plant has been selected to guarantee the speed range, operational flexibility and power projection, survivability, efficiency, and environmental print in response to the demanding operational requirements. Two gas turbines and two diesel engines have been sized to allow a maximum speed of 29 Kn and cruise speed of 18 Kn, respectively, at the end-of-life displacement and requiring an operation range of 7000 nautical miles at cruising speed. Eventually, the patrolling speed is guaranteed by two electric motors powered by four identical diesel generators. In addition, the integration of a Battery Energy Storage System, as discussed in Section 3, is proposed as a backup to meet the redundancy requirements while reducing fuel consumption. The generation and propulsion plant ensure the electric power supply, transformation, distribution, and usage. At the same time, it provides propulsion power to the ship not only via purely mechanical systems but also by electric motors. According to the "$n+1$" redundancy principle, three generators out of four provide the required electric power at cruising speed. The generation plant is then divided into two power plants of two diesel generators each. A BESS is fully integrated inside the drive of each squirrel-cage electric motor, and it is divided into four ESMs directly connected in pairs to the DC-links of the drives. Each BESS is sized according to the required electric power in emergency conditions when one of the generators fails. In particular, the BESS delivers the necessary power for 20 minutes to guarantee enough time to start up another generator. The proposed architecture allows high efficiency for a wide range of speeds, leveraging the Lithium-ion battery pack to keep the generators working in MGO mode at low speed. Figure 3 shows the architecture. Notice that only the starboard shaft line is shown, the portside being conceptually similar. The main technical data of the machinery are reported in Table 1.

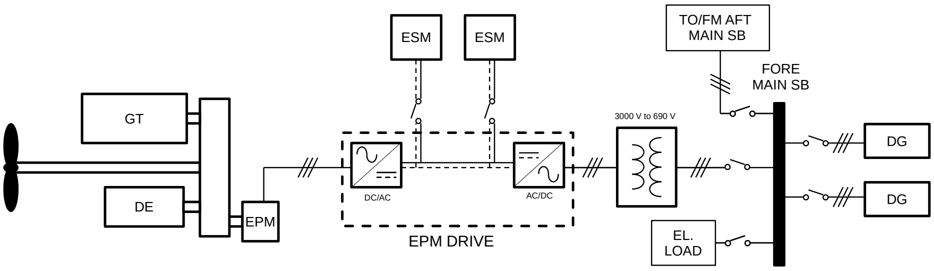


Figure 3. Layout of the proposed propulsion scheme (only the starboard shaftline is shown).

Table 1. Sizing of the main propulsion and generation machinery

Gas turbines	$2 \times 30600 kW$ @ $3600 rpm$, $220 g/kWh$ min.
Prop. Diesel engines	$2 \times 7280 kW$ @ $1150 rpm$, $188 g/kWh$ min.
EPM	$2 \times 1120 kW$ @ $880 rpm$
Diesel generators	$4 \times 2240 kW / 2150 kWe$ @ $1800 rpm$, $188 g/kWh$ min.
BESS	$4\times$ ESM $(3240 Ah$ @ $972 V)$
ESM	$18(s) \times 54(p)$ modules $(60 Ah$ @ $54 V)$

5. Dynamical modeling of the propulsion and power generation plant

New design configurations must be backed by accurate quantitative data to evaluate the vessel's operational performance. Stationary calculations provide the first essential indications for the integrated system sizing but do not provide information on the performance in the time domain. Dynamical simulation can be beneficial in the design phase to assess the behavior of the propulsion system in some reference scenarios dominated by dynamical effects. For instance, dynamical simulations come in handy to verify a crash stop or an acceleration requirement. For this study, dynamical simulation is helpful to evaluate the behavior of the BESS backup capability when a generator shuts down unexpectedly in a near black-out scenario.

The surge dynamics of the hull is described by means of the first cardinal equation of classical mechanics:

$$(M+M_a)\dot{u}(t) = (1-t_{df})T - R_T \tag{1}$$

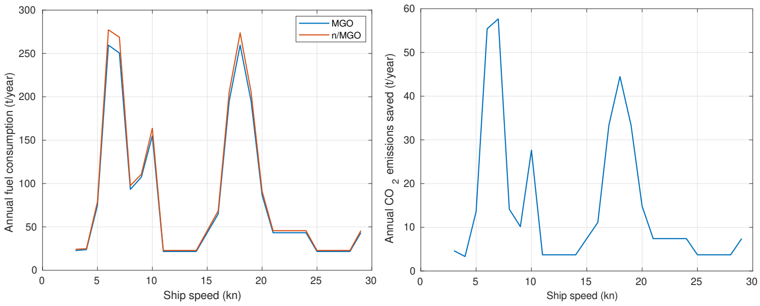
Where M is the displacement at delivery conditions, M_a is the added mass, $u(t)$ is the ship speed, R_T is the hull resistance, T is the total thrust delivered by the propellers, t_{df} is the thrust deduction factor.

The dynamical model of the shaft line is based on the second cardinal equation of classical mechanics:

$$2\pi J_{TOT}\dot{n}(t) = \eta_{mec} \cdot iQ_B - Q_D \tag{2}$$

where n is the shaft resolution speed, J_{TOT} is the total inertia of the rotating masses, Q_B is the brake torque, $Q_D = Q_O/\eta_R$ is the torque required by the propeller, i is the reduction gear and η_{mec} accounts for the mechanical losses.

Diesel generators are modeled by using ideal sources, electric lines properties are represented by lumped parameters, while equivalent circuits allow modeling the trans-



(a) (b)

Figure 4. Annual fuel consumption 4(a) and CO_2 emission savings 4(b) in MGO mode vs. ship speed

formers. The squirrel cage induction motors are modeled by lumped parameters. A fourth-order state-space model represents the electrical part of the motor, while the mechanical part is modeled as a second-order system implementing the second cardinal equation of classical mechanics. The BESS is modeled according to Shepherd's model [8,9].

The electric propulsion control system is a standard propeller speed and pitch controller, acting on the motor torque and the p/D ratio of each CPP. The control strategy of the motor is based on the scalar control of the U/f ratio.

6. Results

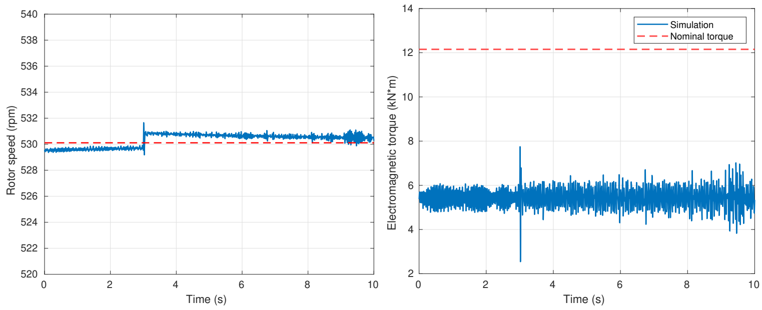
6.1. Fuel consumption and emission assessment

According to the operating profile (Figure 1), fuel savings achieved in MGO mode can be estimated and compared to conventional generator operation. Assuming that the ship sails for 3500 hours each year, a total of 1190 hours per year in electric propulsive mode can be estimated, that is the 34% of the total period at sea on an annual basis. Two operational conditions have been analyzed and compared: the MGO mode, where two or three generators are in motion depending on the power request, and the n/MGO mode, where one extra generator runs with an $n+1$ redundancy. The annual fuel consumption is evaluated using the specific fuel consumption map of the diesel engines used for generation.

The annual fuel consumption throughout the speed range is shown in Figure 4(a) for both the operating modes. The number of generating sets in motion in each condition is calculated according to the requested electric power at the primary grid.

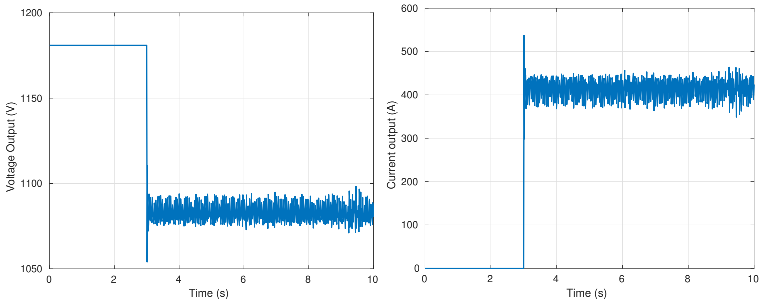
The overall savings throughout a minimum lifetime of 30 years, assuming a fuel cost for the Navy of 0.45 €/l and considering the fuel consumption occurred only in cruising operational condition, can be estimated at over 20 million euros. Eventually, the reduction of fuel consumption leads to a decrease of pollutant gas emissions such as CO_2, NO_x and SO_x. As an example, the mass of CO_2 can be assessed via the emission factor, E_F [10]. Figure 4 presents the annual emission savings depending on the ship speed. The reduction of CO_2 emissions can be estimated at 398 t every year when the ship operates in electric mode.

6.2. *Time domain analysis*



(a) Rotor speed

(b) Time history of the electromagnetic torque (C_n indicates the nominal torque value at 10 *kn*)



(c) Voltage at the terminals of the ESM

(d) Current at the terminals of the ESM

Figure 5. Dynamical simulation results

Time-domain analysis of the ship performance during navigation with electric propulsion in MGO mode has been performed using dynamical simulation techniques. The simulations were carried out at the patrolling speed of 6 *kn* . The simulation started at the time $t_0 = 0\ s$, then at the time $t_1 = t_0 + 3\ s$ one generator out of three failed. Immediately, the batteries were connected to the grid. The ship's speed remained constant, given the significant mass inertia properties of the propulsion system. As shown in Figure 5(a), the motor speed followed the setpoint as expected. Figures 5(c) and 5(d) show the voltage and current at the terminals of each ESM of the BESS. Notice that the voltage at the ESM terminals is equal to its no-load value during the first three seconds of the simulation when the battery is not connected to the grid. At t_1, the ESM was connected to the grid; consequently, the voltage oscillated over time around the corresponding value on the discharge curve at the rated current. Similarly, the current was initially zero in the first three seconds of the simulation, while it oscillated around a value close to the nominal current for $t > t_0 + 3\ s$. The simulations showed the performance of the designed system in the time domain, validating in an operating condition the sizing process carried out during the design phases. Furthermore, the integrated system successfully managed transient operation and presented a stable behavior in steady-state conditions.

7. Conclusions

This paper presented an innovative hybrid propulsion layout using Battery Energy Storage Systems of a flexible new generation naval ship Destroyer (DDX, Destroyer, Experimental). Even if storage systems have found increasing interest and applications on merchant ships during the last few years, the proposed modular solution represents an innovation in the state-of-the-art hybrid propulsion systems for big, front-line naval ships. As a common practice, navy ships keep running one generator more than necessary to match reliability requirements. Therefore, the proposed solution relies on a BESS as a backup power source to maintain reliability requirements in MGO (Minimum Generator Operation) mode. The workflow of the design process has been discussed to illustrate the intricate decision-making process behind each choice. Moreover, dynamical simulation has been used to verify the time-dependent behavior of the designed system in challenging transient conditions. The fuel consumption performances of the proposed solution have been compared to the conventional plant operating mode, showing a potential saving of over 20 million euros through the ship's life cycle. In addition, results showed that MGO mode for generation plants could significantly reduce pollutants and greenhouse gas emissions released into the atmosphere every year. Eventually, time-domain simulations showed a stable operating mode for BESS and electric motors, accomplishing the design requirements. Moreover, the simulation model avoided black-out in a diesel generator failure scenario.

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