Battery Solutions and Aging Process Simulation for Maritime Electric Propulsion

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***Abstract*— Climate change poses a significant challenge to human life and ecosystems. Today, the maritime industry faces increasing pressure to reduce its carbon footprint, with all stakeholders required to comply with the International Maritime Organization (IMO) regulations. To support the design of innovative ships, the Siemens Simcenter portfolio provides solutions that meet IMO specifications. Electrical propulsion systems are particularly important for vessels operating in Emission Control Areas (ECAs), where carbon emissions can be significantly reduced. The main objective of this article is to simulate a fully hybrid electric ship propulsion architecture and evaluate the aging process of its battery system. Battery capacity loss over the system's lifespan is determined using aging test data to calibrate an empirical aging law.**

Keywords—hybrid marine power system, battery aging, Siemens Simcenter Amesim simulation

I. Introduction

The shipping industry is increasingly shifting its focus towards electrification, decarbonization, and greener solutions. Following trends in other sectors, hybrid electric propulsion systems have been proposed and implemented in ships to improve efficiency, reduce carbon emissions, and lower overall operational costs by combining traditional mechanical propulsion with electric propulsion [1].

In recent years, analyses have been conducted on various types of hybrid marine propulsion systems to understand ship behavior under different operating and loading conditions and to optimize the hybrid system's cost function. Previous studies have extensively examined several marine propulsion systems, specifically diesel–mechanical powered [2, 3] and diesel–electric powered vessels [2, 4–6].

Different ship propulsion architectures, illustrated in Figure 1, can be grouped as follows: Diesel Mechanical, Diesel Mechanical Assist, Diesel on Demand, and Hybrid.

The *Diesel Mechanical architecture* consists of two internal combustion engines connected to two electric machines that operate as generators. These generators supply power to the ship's electrical load. The other two internal combustion engines are mechanically connected to the propeller through a gear ratio and provide propulsion power for the ship.

The *Diesel Mechanical Assist architecture* includes two internal combustion engines connected to two electric machines that work as generators. These electric generators charge the battery that powers the electric load of the ship, and the electric motors dedicated for the ship propulsion.

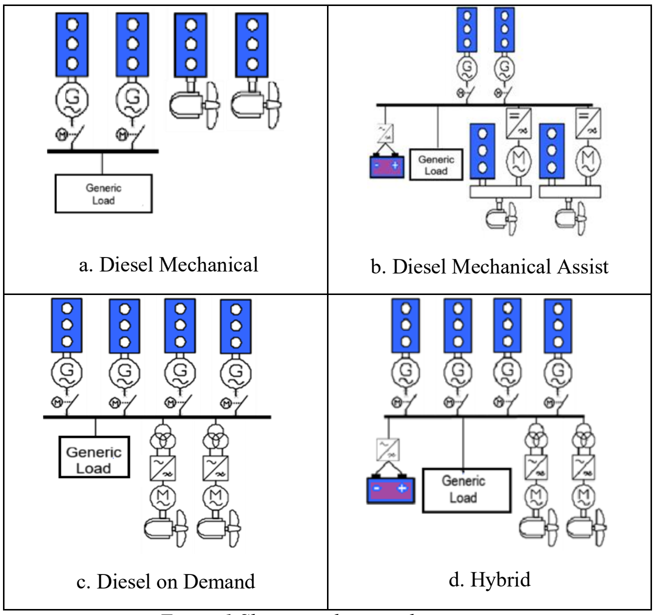

Figure 1 Ship propulsion architectures.

The other two internal combustion engines are mechanically connected to the propeller, each one in parallel with an electric machine that works as a motor. These electric motors assist the two internal combustion engines for ship propulsion.

The *Diesel on Demand architecture* is composed of four internal combustion engines connected to four electric machines that work as generators. These electric generators provide power to two electrical motors that are mechanically connected to the propellers with a gear ratio.

The *Hybrid architecture* includes four internal combustion engines connected to four electric machines that work as generators. These electric generators charge the battery that powers the electric load of the ship, and the electric motors dedicated for the ship propulsion. These four internal combustion engines are controlled to maintain the state of charge of the battery at a specific value. The battery

State of Charge (SoC) set point is different for each internal combustion engine. The propulsion of the ship is provided by two electric motors that are mechanically connected to the propellers with a gear ratio. There are also considered the electrical load and electrical losses.

Hybrid diesel propulsion combines the benefits of both electrical and mechanical components highlighted. Diesel–electrical propulsion has advantages in its ease of maintenance since electrical compliances occupy a smaller footprint as compared to mechanical components and allow for more flexibility in the positioning of the thrusters or any other mechanical equipment, [7-9].

II. Modelling of Hybrid Propulsion System

The virtual ship model features a hybrid electrical power system integrating two gensets in parallel with a Battery Electrical Storage System (BESS) to provide fully electrical propulsion. Each genset comprises two internal combustion engines connected to electric machines functioning as generators, supplying power to two propulsion motors and managing overall energy distribution. A Power Management Controller regulates the motors according to a user-defined mission profile, while energy allocation accounts for all onboard electrical consumption, including constant loads such as hotel systems or steady resistances. The propulsion motors are connected to the propellers via a gear ratio, driving the vessel through the water.

The primary components of the model include:

- Ship resistance and propellers: Represent the hull and propulsion system, including navigation equipment.
- Battery model: Implemented in Simcenter Amesim, it powers the propulsion system and buffers the gensets.
- Power electronics: Manage DC/AC power distribution and accommodate variable load demands.
- Hotel load and shore connection: Enable accurate power budget analysis and comprehensive energy management.
- Gensets: Serve as the primary electrical power sources; proper sizing is critical for system efficiency.
- Control systems: Regulate genset operation based on state of charge (SOC) and navigation requirements, ensuring adherence to the reference speed profile.

A detailed schematic of the model in Simcenter Amesim, showing interconnected components and control systems, is presented in Figure 3 [10,11].

The ship model has a mass displacement of 720 tons and a length between perpendiculars of 75 m. The statistical Barrass method, based on these parameters, is employed to compute the resistance force arising from the frictional interaction between the ship's hull and the water. This method also allows the inclusion of additional factors such as hull condition, fouling, or severe weather through two coefficients: the hull condition coefficient and the sea condition coefficient.

The vessel is equipped with two fixed-pitch propellers responsible for forward and backward motion. Each propeller has four blades, a diameter of 2.2 m, and a blade area ratio of 1. The thrust coefficient (C_t) and torque coefficient (C_q) are determined using the Woodward method [12]. Each propeller is driven by a three-phase electric motor with constant efficiency and power factor. The torque input for each motor is computed by a PID-based speed controller.

The ship operates on a DC electrical grid, an emerging technology in modern shipbuilding due to its advantages over AC grids [13]. DC grids enable better integration with renewable energy sources and reduce conversion stages, lowering equipment requirements and improving overall efficiency, thereby increasing fuel-saving potential. A switchboard serves as the central hub for power distribution, connecting power sources to electrical loads throughout the ship while providing protection against short circuits, overcurrent, and ground faults.

Because the generators and electric motors use three-phase AC current while the grid operates on DC, inverter units are required to convert between the two. As illustrated in Figure 2, each inverter unit comprises three static inverters, one per phase, implemented using the Simcenter Amesim supercomponent feature to aggregate multiple components into a single entity. This design allows the inverter unit not only to convert DC to AC but also to operate as a rectifier, converting AC to DC when needed.

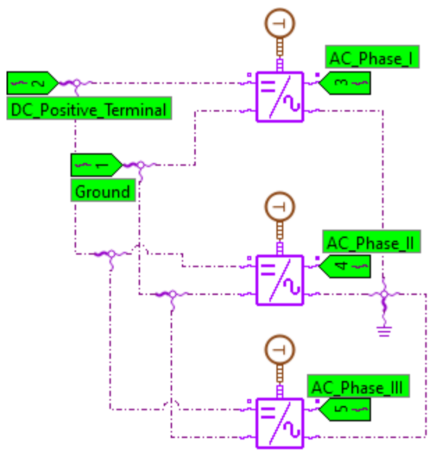

Figure 2 Three phase inverter unit.

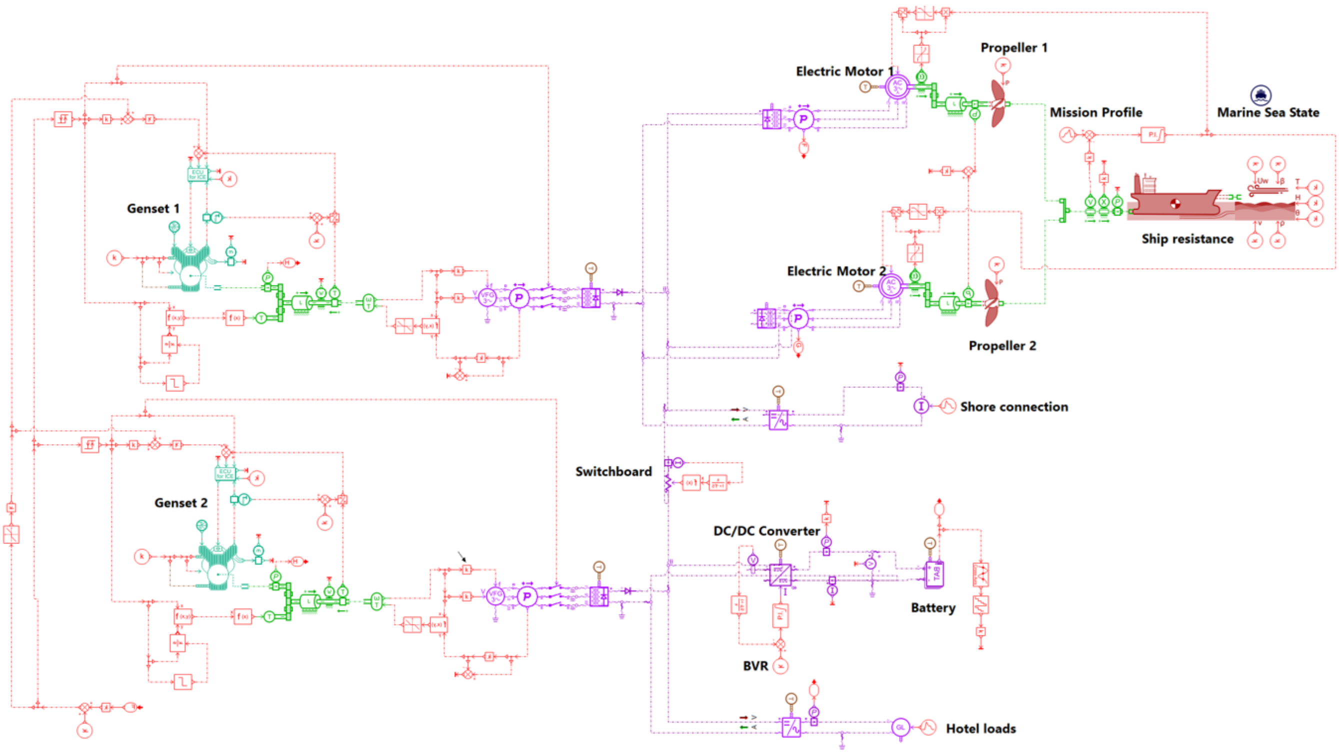

Figure 3 Sketch of the Hybrid Propulsion Ship Model

A DC/DC converter is used to regulate the current flowing through the BESS, as shown in Figure 4. Since the battery voltage varies with the state of charge (SOC), the converter ensures that the DC bus maintains a Base Voltage Rating (BVR) of 1000 V. The required battery current is calculated using a PI controller, based on the error between the BVR and the actual DC bus voltage.

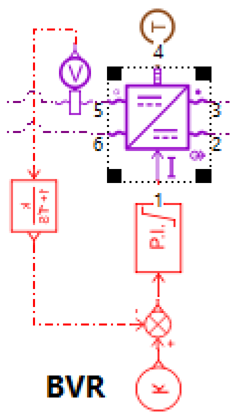

Figure 4 DC/DC converter with PID controller

The BESS submodel itself is an advanced equivalent circuit capable of reproducing the dynamic voltage behavior of the battery, as well as the heat generated during charging and discharging, as illustrated in Figure 5. The model is based on the equivalent circuit configuration, which accurately represents the electrical and thermal characteristics of the battery system.

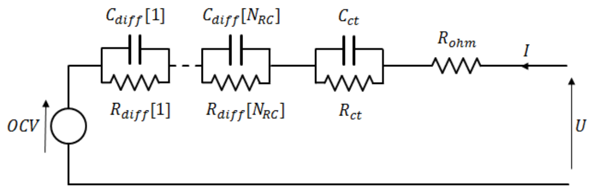

Figure 5 Dynamic equivalent circuit model of battery cell

The battery can be represented in a very simple form, considering only basic phenomena such as open-circuit voltage and ohmic resistance. However, more advanced features can also be modeled, including faradaic efficiency, hysteresis, and aging effects. In this study, aging is included to estimate both calendar and cycle-related degradation of the battery's capacity and internal resistances.

The battery uses Nickel Manganese Cobalt (NMC) chemistry with a high nickel content. Its configuration consists of 162 cells in series and 100 cells in parallel, resulting in a nominal voltage of 600 V, a peak power output of 3000 kW, and an energy capacity of 2000 kWh. Each cell has a capacity of 35.57 Ah. The total mass of all cells is 6,580 kg, representing less than 1% of the ship's mass displacement.

The BESS functions as a buffer between the gensets and ship electrical loads, ensuring stable power for propulsion and hotel loads while allowing evaluation of battery aging and performance.

III. Battery Aging Simulation Model

Battery aging involves both capacity degradation and increases in internal resistance, leading to reduced energy storage capacity and efficiency over time.

To predict battery capacity loss over its lifespan, two main modeling approaches are commonly used in the literature [14]: the *physical* approach and the *empirical* approach. Each has its advantages and limitations. Unlike the physical approach, the empirical approach does not require a complete understanding of the underlying aging mechanisms; only aging test data are needed to calibrate the empirical aging law.

The Battery Aging Identification Tool [14–17], available in Simcenter Amesim, provides a user-friendly graphical workflow (Figure 6) that allows quick conversion of test data into empirical aging models.

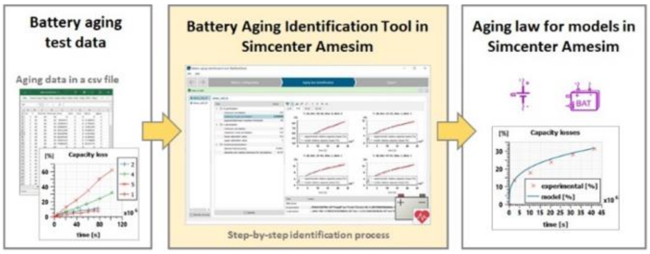

Figure 6 Battery Aging Identification Tool

• The tool takes battery experimental aging test data as input. These data describe the battery capacity loss over time under different conditions, such as varying states of charge (SoC), ambient temperatures, and current rates. Experimental tests on individual battery cells can provide these data.

• The tool guides the user through a step-by-step identification process, including data import, aging law determination, and export of the aging law to the battery model.

• The output is the identified aging law, expressed as a function of SoC, C-rate, and temperature. This aging law can be directly applied to the battery model in Simcenter Amesim.

The generic empirical aging law identified by the tool is described by the equation below:

$$Q_{loss} = B_{coef} . t_{yr}^{z_{coef}} \quad (1)$$

where:

- Q_{loss} is the relative capacity loss in [%].
- B_{coef} is the aging prefactor B [%/year]. It depends on the state of charge, C-rate current and temperature.
- z_{coef} is the aging exponent z. It depends on the state of charge, C-rate current and temperature.
- t_{yr} is the aging time [year]

When the SoC, temperature and C-rate current are not constant, the relative capacity loss is obtained by integrating its derivative over time. The derivative of the relative capacity loss is defined as follows:

$$\frac{dQ_{loss}}{dt_{year}} = B_{coef} \cdot z_{coef} \cdot \left(\frac{Q_{lossSat}}{B_{coef}}\right)^{1-\frac{1}{z_{coef}}} \quad (2)$$

B_{coef} and z_{coef} are the result of a saturation functions applied to polynomial expression B_{poly} and z_{poly} .

IV. Simulation Results and Conclusions

The main parameter in the simulation of a hybrid ship propulsion architecture is the imposed speed profile over time, which must be achieved during the ship's mission. The Mission Profile Controller compares the imposed speed profile with the actual ship speed, determining the torques required by the electric motors driving the propellers.

The battery functions as a power buffer between generated and consumed energy, enabling the engines to operate at their highest efficiency. The Diesel-Electric Hybrid control system is based on battery state-of-charge (SOC) regulation:

- By default, both gensets are OFF.
- When SOC drops below 50%, Genset 1 starts and runs at its optimal operating point.
- When SOC exceeds 90%, Genset 1 stops.
- When SOC drops below 20%, Genset 2 starts and runs at its optimal operating point.
- When SOC rises above 65%, Genset 2 stops.
- If SOC falls below 10%, both gensets operate at optimal operating power plus half the difference between maximum and optimal engine power.

Two simulation cases were studied using different generator types: run1 – MTU 1320 kW and run2 – MTU 1760 kW, with all other parameters and inputs identical. Figure 7 shows the mission speed profile alongside the actual ship speed over a mission duration of approximately 1×10^5 seconds (27.77 hours). The same speed profile was applied in both simulations.

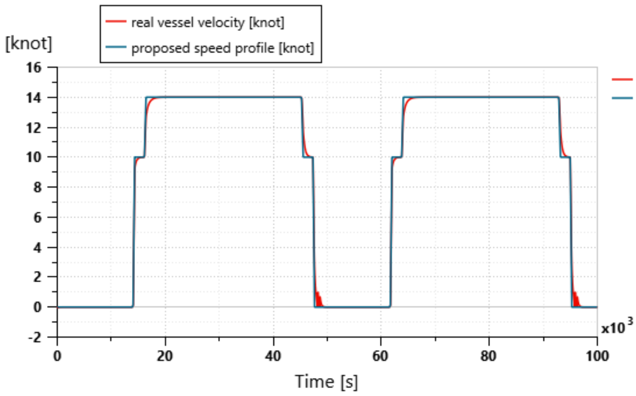

Figure 7 Mission speed profile vs. actual vessel velocity

The results indicate that the ship's power resources—electric generators and battery—successfully maintain the proposed speed profile. Figures 8 and 9 show the mechanical power consumed by the generators and the electrical power exchanged with the battery during charging and discharging processes. Negative battery power values correspond to discharging, while positive values indicate charging.

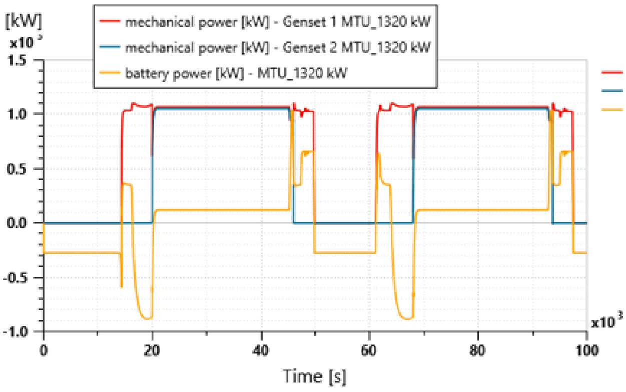

Figure 8 Engine mechanical and battery powers MTU 1320 kW

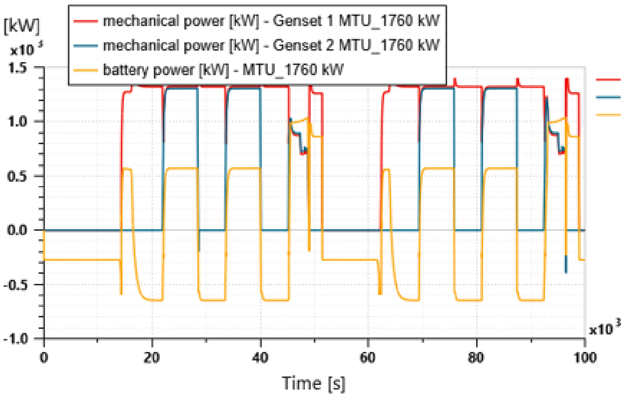

Figure 9 Engine mechanical and battery powers MTU 1760 kW

The battery cell model (Figure 2) includes an empirical aging law derived from experimental data from the MOBICUS project [18]. Accelerated aging tests were conducted on 100 NMC/C HE battery cells at different temperatures, states of charge, and C-rates, with capacity loss measured periodically. The model allows evaluation of cyclic aging resulting from repeated charge-discharge cycles. Figure 10 presents the cyclic currents for the two generator configurations, and a counter in the simulation tracks the number of cycles.

For both simulations, battery capacity loss is calculated based on the number of cycles over the mission duration (1×10^5 and 2×10^5 seconds, corresponding to 27.77 and 55.55 hours). Figures 11 and 12 show the evolution of capacity loss over time, expressed as a percentage of the battery's initial charge capacity. It is observed that, for identical speed profiles and cycles, capacity loss progresses nonlinearly over time.

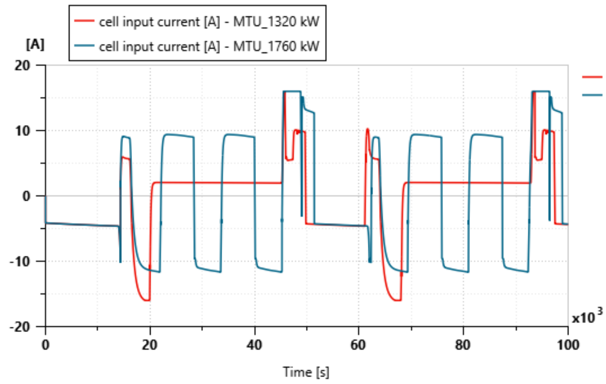

Figure 10 Battery cell input currents

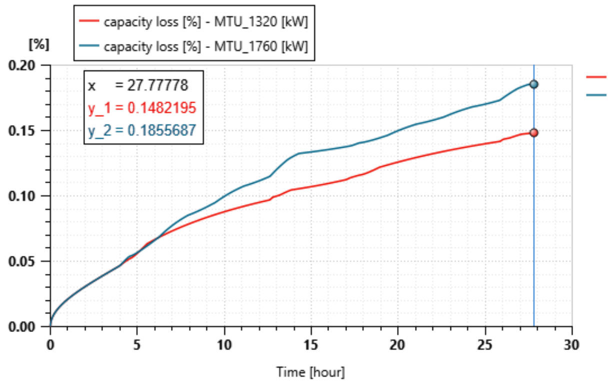

Figure 11 Battery capacity loss 27. 77 hours

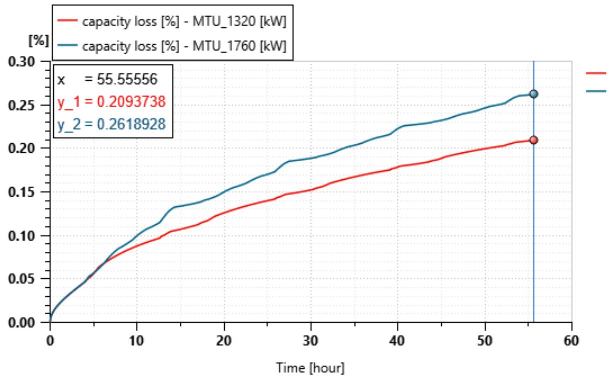

Figure 12 Battery capacity loss 55.54 hours

V. Conclusions

The simulation battery model uses an empirical aging law to evaluate cyclic degradation for both generator types. Results show that the ship's power system reliably meets the imposed speed profile, with the battery effectively buffering power, while capacity loss over time exhibits nonlinear behavior. This study focused on applying an experimentally calibrated battery aging model to simulate hybrid ship propulsion under a defined mission profile and specific sea conditions. Future work will extend this analysis to evaluate battery capacity loss across different propulsion architectures, speed profiles, and variable operational conditions that affect ship resistance and overall energy consumption.

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