Development of Operational Strategies for Optimal Usage of Batteries Onboard Commercial Vessels

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Abstract— This paper explores strategies to optimize and extend the lifespan of onboard battery systems in commercial vessels. As sustainability becomes a priority in the maritime industry, battery technology for auxiliary power and peak shaving is gaining traction. This study discusses the challenges and opportunities of integrating this technology, including energy storage limitations, battery health, charging infrastructure, and costs. It highlights cleaner operations, reduced emissions, fuel efficiency, and improved vessel maneuverability as potential benefits. The importance of operational strategies for battery optimization is emphasized, considering factors like charging cycles, depth of discharge, operating temperature, safety, reliability, and adaptability. The paper presents a framework for developing these strategies, identifying key factors such as Full Equivalent Cycles (FEC), State-of-Charge (SoC), State-of-Health (SoH), and temperature effects. Commercial vessels are classified based on power groups with specific battery needs for each group. This work asserts that operational strategies are crucial for maximizing onboard battery system benefits. It advocates for systematic implementation to achieve sustainability targets and economic and operational advantages in the maritime industry.

Keywords— Ship Electrification, Battery Systems, Commercial Vessels, Operational Strategies, Optimization, Sustainability, Maritime Industry.

1. INTRODUCTION

1.1. Motivation: Growing focus on sustainability in the maritime industry

The maritime industry plays a vital role in global trade, but its operations have also been a significant contributor to greenhouse gas emissions and environmental pollution. In recent years, there has been a growing global focus on sustainability, prompting the maritime industry to adopt cleaner technologies and operational practices [1].

1) *This heightened awareness is driven by several factors*: The International Maritime Organization (IMO) urges organizations and governments to promptly implement measures to achieve zero carbon emissions from maritime transportation. Authorities are implementing more stringent regulations, such as the Sulfur Emission Control Area (SECA) and the Energy Efficiency Existing Ship Index (EEXI). These restrictions drive organizations to prioritize alternate fuels and renewable energy sources.

2) Climate change concerns: The increasing urgency of addressing climate change has spurred societal and industrial awareness of the environmental effects of maritime transportation [2]. Corporations are seeking ways to reduce their carbon footprint and have a positive impact on the environment for long-term sustainability [3].

3) Economic benefits: Investing in sustainable technologies can lead to long-term cost savings through reduced fuel consumption and improved operational efficiency [4]. Additionally, companies that embrace sustainability gain a competitive edge by demonstrating their commitment to environmental responsibility.

As a result of these motivations, the maritime industry is witnessing a surge in innovation and adoption of sustainable technologies, including battery systems for onboard power and peak shaving. However, to maximize the benefits of these technologies, effective operational strategies are crucial to ensure optimal battery usage, minimize negative environmental impact, and achieve long-term cost efficiency.

1.2. Challenges and opportunities of onboard battery systems

While battery technology presents a promising avenue for cleaner maritime operations, integrating them onboard vessels presents both challenges and opportunities.

1.2.1. Challenges

- *Limited energy storage capacity:* The current battery technology, due to its relatively low energy density, has major limitations on the amount of energy it can store when compared to traditional marine fuels. This not only limits the duration and range that vessels can operate solely on battery power, but also poses challenges in terms of the extra weight and space required by battery systems. These limitations collectively prohibit the broad implementation of fully electric propulsion in maritime vessels.
- *Battery health management*: Maintaining optimal battery health throughout its lifespan is crucial for maximizing performance and efficiency [5]. This requires careful monitoring of factors like temperature, charge/discharge cycles, and aging.
- *Charging infrastructure:* Shoreside charging infrastructure for large commercial vessels is still under development in many ports [6]. Additionally, integrating renewable energy sources for onboard charging presents technical and logistical challenges.
- *Higher upfront costs:* Battery systems and their supporting infrastructure currently have a higher upfront cost compared to conventional propulsion systems [7]. However, advancements in technology and the ability to produce on a larger scale are anticipated to reduce these costs in the future.

1.2.2. Opportunities

- *Reduced emissions and cleaner operations:* Batteries offer a significant reduction in greenhouse gas emissions and air pollutants compared to traditional diesel engines [8]. This can lead to cleaner air, safety marine life and improved environmental health in port cities and coastal regions.
- *Fuel efficiency and peak shaving:* Batteries can be used to supplement onboard power needs, reducing reliance on main engines and enabling peak shaving during periods of high energy demand. This translates to lower fuel consumption and operational costs. Also, electric motor power versus speed curve of an electric propulsion ship gives a better energy efficiency with respect to fuel versus ship speed [9].
- *Integration with renewable energy:* Onboard batteries can be charged using renewable energy sources like solar panels or shoreside wind power. This allows vessels to further reduce their environmental impact by utilizing clean and sustainable energy sources.
- *Improved vessel maneuverability:* Battery systems can provide instant power for improved maneuverability in ports and during close-quarter operations. This can enhance safety and efficiency in these critical scenarios.

By effectively addressing the challenges and capitalizing on the opportunities presented by onboard battery systems, the maritime industry can move towards a more sustainable future.

1.3. Importance of operational strategies for battery optimization

While onboard battery systems offer significant environmental and economic benefits, maximizing their effectiveness hinges on implementing well-defined operational strategies.

1) Optimizing Battery Lifespan: Effective strategies consider factors like charging cycles, depth of discharge, and operating temperature to minimize battery degradation and extend its lifespan. This translates to long-term cost savings and reduces the environmental impact associated with battery production and disposal.

2) Maximizing Efficiency: Strategic planning for charging and discharging cycles ensures batteries are used efficiently. This might involve prioritizing shoreside charging when available, utilizing renewable energy sources, and optimizing onboard energy management systems to minimize reliance on auxiliary engines.

3) Minimizing Operational Costs: By optimizing battery usage, operational costs can be significantly reduced. Strategies can focus on minimizing fuel consumption through peak shaving and efficient power management, leading to long-term financial benefits for shipping companies.

4) Ensuring Safety and Reliability: Ensuring safety is the highest priority while dealing with onboard battery systems. Operational strategies must include robust procedures such as continuous monitoring of crucial parameters like temperature, battery cell health enables real-time identification of possible difficulties. Additionally, periodic inspections and maintenance which include conducting temperature tests and cleaning battery ventilation systems, ensure optimum performance and reduce the likelihood of failures

5) *Adaptability to Different Scenarios:* Effective strategies consider the specific requirements of each vessel and its operational profile. Factors like voyage length, cargo type, and port facilities all influence battery usage. For longer voyages, strategies might prioritize maximizing battery capacity utilization, potentially involving deeper discharging cycles when necessary. Variant cargo types can have higher energy requirements depending on cooling demands. Strategies might involve incorporating larger battery capacities or prioritizing shoreside charging at ports with appropriate infrastructure. Tailored strategies ensure optimal battery performance, regardless of the operational situation.

In conclusion, operational strategies are not merely an afterthought; they are critical components for unlocking the full potential of onboard battery systems. Implementing these strategies allows the maritime industry to achieve its sustainability goals while maximizing the economic and operational benefits of battery technology.

2. Framework for Developing Operational Strategies

2.1. Factors influencing battery usage on commercial vessel

Battery usage on commercial vessels is influenced by many factors that can significantly impact their performance and lifespan. These key factors include the number of Full Equivalent Cycles (FEC), State-of-Charge (SoC), State-of-Health (SoH), and the effects of temperature. Understanding and managing these parameters is crucial to optimize battery operation and extend their service life.

2.1.1. Number of Full Equivalent Cycles (FEC)

The term 'cycle life' represents the total charge and discharge cycles a battery can sustain before a significant decrease in its capacity. It is a vital indicator of a battery's overall performance and lifespan. The concept of 'equivalent cycles' is employed to identify the cycle life in real-world conditions. FEC considers the variations in battery usage patterns and depth of discharge, symbolizing the accumulated wear and tear on a battery as if it underwent a particular number of complete charge and discharge cycles. Fig. 1 illustrates a standard diagram showing the potential number of cycles within the lifespan as a function of depth of discharge.

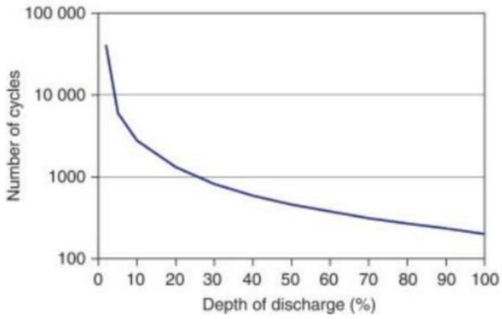

Figure 1 - Diagram for the number of cycles [10]

2.1.2. State of Charge (SoC)

Typically, batteries, including those of the lithium-ion variety, have an ideal operating range for their SoC, often recommended to be between 20% and 80%. Maintaining the SoC within this optimal range is beneficial for extending the battery's lifespan. However, consistently keeping a high SoC (almost 100%) can adversely affect the lifespan of the battery due to induced stress, accelerated chemical aging, and eventual capacity degradation. Similarly, holding a battery at a very low SoC (near 0%) for extended periods can also cause substantial damage, leading to self-discharge, possible deep discharge, and stress.

2.1.3. State of Health (SoH)

SoH refers to the current condition of a battery, specifically indicating its remaining capacity. Research efforts are underway to accurately determine this parameter. The gradual decline in the energy storage capacity and power output of batteries over time necessitates the assessment of their SoH to ensure safe and efficient operation within onboard battery systems. Once the health indicator surpasses a predetermined threshold, it becomes imperative to remove the battery from the energy storage system [11]. The case study ELECTRA explores an operational strategy to maximize SoH and extend battery lifespan. This strategy involves a methodology for maintaining SoC within a predefined range.

2.1.4. Temperature Effects

Temperature significantly affects battery performance, shelf life, charging, and voltage control. Higher temperatures induce more chemical activity inside a battery than lower temperatures. Hence, the capacity of a battery drops when the ambient temperature is too low. Conversely, high temperatures can speed up chemical reactions, while low temperatures can obstruct ion mobility, affecting a battery's performance and lifespan. For the majority of batteries, the suggested temperature range is between 15 ºC and 30 ºC. Operating a battery outside this range, in extremely cold or hot temperatures, can drastically reduce its cyclic life. Therefore, it is essential to take temperature effects into account when choosing the most appropriate charging and discharging conditions for batteries to enhance their lifespan.

These factors have a significant impact on battery aging and performance and must be carefully managed to ensure the longevity and reliability of the battery systems on commercial vessels.

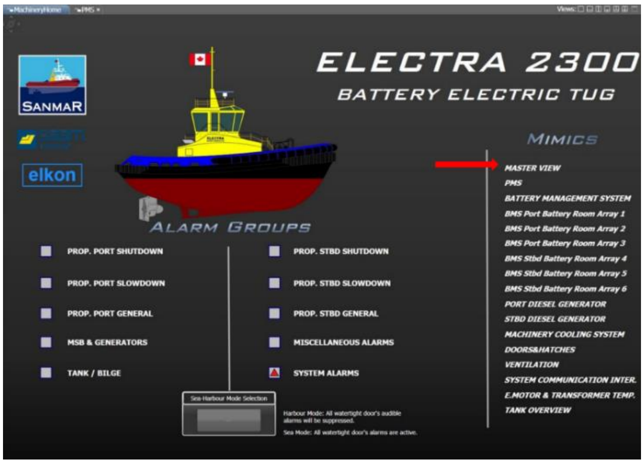

Figure 2 - Electra 2300 Interface

2.2. Classification of commercial vessels based on power groups

2.2.1. Small vessels

- Examples: Passenger ferries on short routes, fishing boats, tugboats
- Characteristics: relatively low propulsion power for maneuvering and short-distance travel. Moderate hotel load for basic onboard systems like navigation and lighting. Short operational range, typically returning to port daily or after a few hours.
- Battery needs: Compact and lightweight systems with rapid charging capabilities are crucial. This allows for quick recharging during short layovers or between trips, maximizing operational efficiency. Battery technology with high discharge rates is also essential to meet peak power demands during acceleration or maneuvering.

2.2.2. Medium vessels

- Examples: Offshore supply vessels, cargo ships
- Characteristics: Moderate propulsion power ranging, depending on size and cargo capacity. Variable hotel loads can fluctuate depending on onboard equipment, Moderate operational range, typically requiring refueling or resupply after a few days at sea.
- Battery needs: Modular systems that offer scalability are key. These systems can be configured to provide significant power for longer durations while remaining adaptable to specific vessel needs. The ability to partially recharge during operations, like while offloading cargo, is valuable for extending range and reducing reliance on fossil fuels.

2.2.3. Larger vessels

- Examples: Cruise ships, container ships, bulk carriers
- Characteristics: Very high propulsion power exceeding 5MW is required to overcome water resistance and maintain cruising speed for long distances. High hotel load due to extensive onboard facilities and systems. Long operational range with voyages lasting weeks or even months.
- Battery needs: large-scale battery systems with high energy density and efficiency are necessary to provide enough power for even limited electric propulsion or peak shaving. Focus should be on maximizing usable energy storage while maintaining durability for harsh ocean environments. While full electric propulsion might not be feasible currently due to range limitations, future advancements in battery technology.

2.3. Strategies for battery implementation

2.3.1. ELECTRA

ELKON designed and implemented a Battery Energy Storage System (BESS) interface for the electric tug named after the Electra 2300 design. This case study defines several operational modes for the battery, balancing reliable and safe BESS operation with long-term economic considerations, specifically maximizing BESS lifespan for a better return on investment. These PMS modes are : battery mode, endurance mode, quick charging mode, transit mode, shore charging mode, semi mode, DC bus-tie breaker control in semi mode. In this project, the battery charging algorithm for all PMS modes use recommended SoC values as a reference provided by the battery manufacturer. The recommended SoC values consider the optimal charging and discharging thresholds as the BESS ages.

Table 1 - Recommended SoC% values

SoC% values		
Years	Min SoC%	Max SoC%
1	23	85
2	21.6	86
3	20.1	87
4	18.7	88
5	17.2	89
6	15.8	90
7	14.3	91
8	12.9	92
9	11.4	93
10	10.0	94

2.3.2. NEMOSHIP project demonstration vessels

The NEMOSHIP project, which is one of the projects under Horizon Europe, demonstrates two types of vessels: an off-shore vessel (OSV) from Solstad and a hybrid LNG- battery cruise vessel called Le Commandant Charcot (LCC). Applying the offshore peak shaving approach is crucial to achieve optimal battery use. Unlike off-shore vessel (OSV), Le Commandant Charcot, the ice breaker cruise ship is operated by a different entity. A battery with a capacity of 4.5 megawatts has already been installed. Given that LLC operates in environmentally sensitive regions, it is essential to emphasize the reduction of emissions while developing the battery optimization strategy.

Figure 3 - Normand Drott vessel

Figure 4 - Le Commandant Charcot vessel

Simultaneously, power management algorithms will be developed specifically to control the operation of heterogeneous storage units. In this context, digital twins of the ships will be utilized to realize more efficient battery usage for both ships.

The Digital Twin Module is a key component, which is made to produce accurate simulation data to simulate the behavior of a physical asset, mainly to maximize battery usage. It replicates the real-world functioning of battery systems by building a dynamic virtual model. This module makes it possible to analyze battery performance in detail under various circumstances, which can help determine the most effective charging and usage cycles. It helps with scenario planning, early problem detection, and predictive maintenance for batteries. With the module's assistance, battery management decisions may be made with greater knowledge, which extends battery life and lowers operating expenses. By offering insightful information

on battery performance, deterioration trends, and lifecycle management, the Digital Twin Module makes it possible to develop strategies that optimize the sustainability and efficiency of batteries.
To summarize, the project is to develop strategies for tackling the modifications required by updated safety standards. This includes expanding the integration of Battery Energy Storage Systems (BESS) on board to include both onshore green power supply and charging infrastructure. Additionally, preparations need to be made to prevent emerging threats like cyberattacks [12].

3. OPTIMIZATION TECHNIQUES FOR EFFICIENT BATTERY USAGE

In this section, Elkon introduces a novel DC-DC converter design aimed at minimizing stress on batteries used in high-power applications [13]. Implementation of a DC-DC converter on hybrid power systems for marine applications that incorporates both diesel generators and batteries. The system utilizes a bidirectional DC-DC converter with LCL filter to manage power flow between the batteries and the DC bus. The control strategy for the converter is model-based and includes active damping of the LCL filter to eliminate resonance issues.

3.1. Preserving battery health via simulation results

MATLAB simulations have been performed to show the effectiveness of the H-bridge DC- DC converter with the LCL filter. Fig. 5-6 remains relevant to the summary as it visually demonstrates the significant reduction in output voltage recoil achieved by the proposed converter compared to the classical converter. This reduction in recoil directly contributes to preserving battery health by minimizing stress on the batteries. Fig.6 shows the graphs of the classical DC / DC converter. The RHPZ analysis is performed in an open loop operation by changing the duty cycle through step by step response. The value of the recoil increases as the load current increases, because the right half plane zero approaches the zero point (origin). Fig.7 illustrates the power control scheme for the hybrid power system. The system utilizes model-based control strategy that coordinates power flow between the batteries and the DC bus. The LCL filter plays a crucial role in damping out resonance and ensuring stable operation. The proposed bidirectional DC/DC converter's LCL filter plays a crucial role in achieving near-zero output voltage recoil, as illustrated in Fig. 8. This significant reduction in recoil directly contributes to preserving battery health.

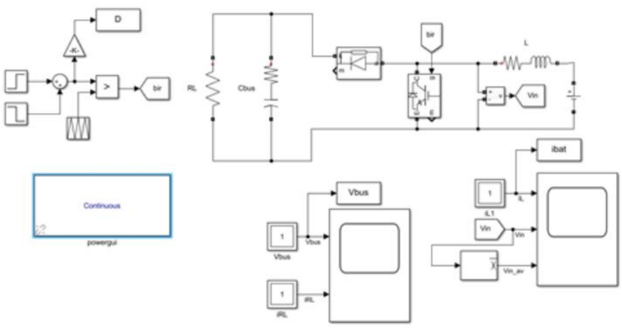

Figure 5 - Power scheme and open-loop control of a conventional DC-DC converter

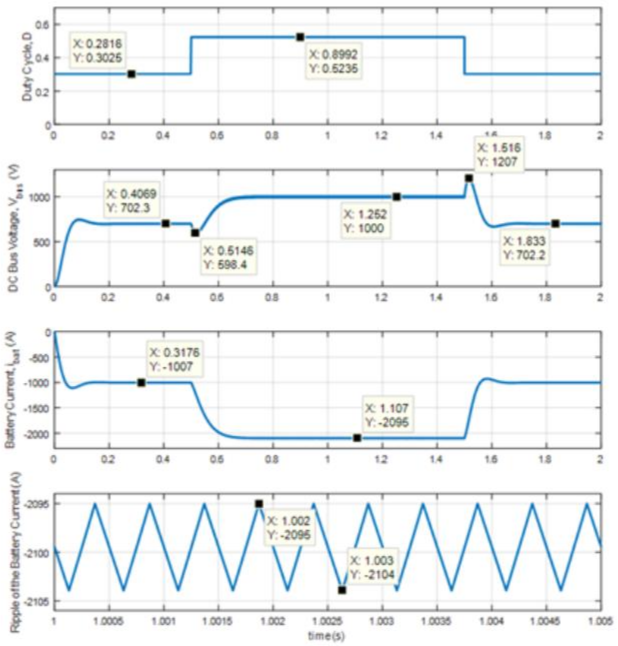

Figure 6 - Conventional DC-DC converter current, voltage, and switching graphs

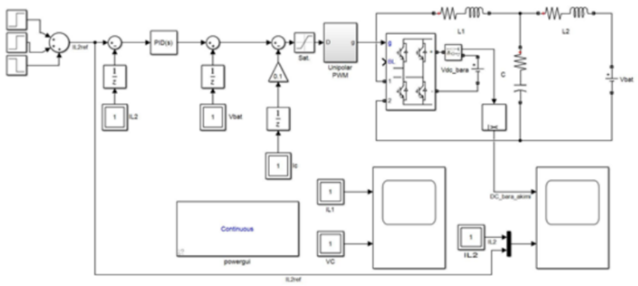

Figure 7 - Power scheme and open loop control of the bidirectional proposed DC-DC converter

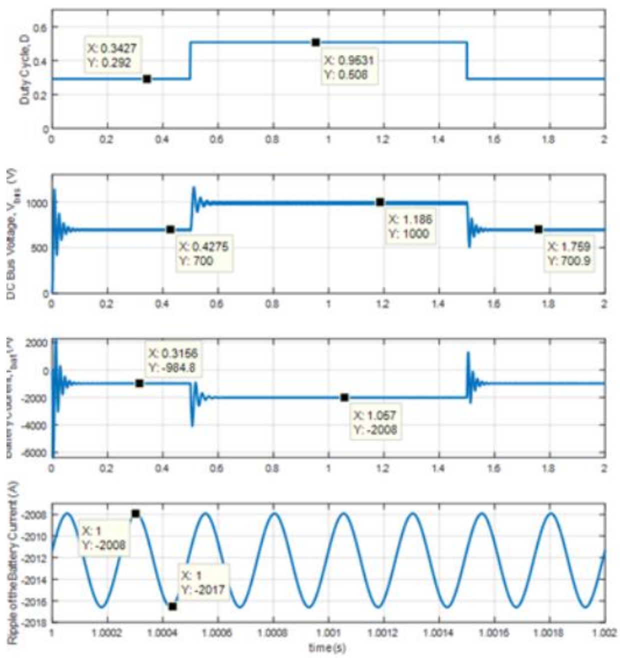

Figure 8 - Proposed DC-DC converter current, voltage, and switching graphs

Reduced Battery Ripple Current: A significant challenge in power electronics is minimizing current fluctuations (ripple current) in batteries. High ripple current can damage batteries and shorten their lifespan. This new converter design utilizes an LCL filter to effectively suppress these fluctuations, protecting batteries and potentially extending their service life. The traditional methods for addressing ripple current, such as adding large capacitors or increasing inductance, come with drawbacks that can increase maintenance needs or replacement costs. This new converter design offers a potential solution to achieve low ripple current without sacrificing efficiency or increasing the physical size and complexity of the system [14]. This could lead to:

- Reduced Battery Maintenance: By minimizing battery strain, the converter could potentially reduce the frequency of required maintenance procedures for batteries in high-power applications.
- Lower Battery Replacement Costs: Extending battery lifespan could lead to significant cost savings over time by reducing the need for frequent battery replacements.

The hybrid power system presented in this paper demonstrates a practical approach to integrating batteries into marine applications while preserving battery health. The control strategies and protection measures implemented ensure that batteries are operated within safe limits, extending their lifespan and reducing maintenance costs. This approach is particularly relevant for applications where batteries are subjected to frequent and demanding charging/discharging cycles.

3.2. Test setup and applied results

In Fig. 9, the project test environment is shown. The system comprises a liquid cooling system, a DC load bank, a lead-acid battery, a 380/690 transformer, and a pre-charging panel test setup. The test environment provides a comprehensive setup for evaluating the performance and safety of the proposed hybrid power system. The proposed topology's power circuit diagram is used to present the results of filter and control methods aimed at suppressing EMI effects and suppressing the fluctuations in battery current. Lead-acid battery tests were carried out first, followed by lithium battery tests. The lithium battery charging and discharging application is shown in Fig. 10.

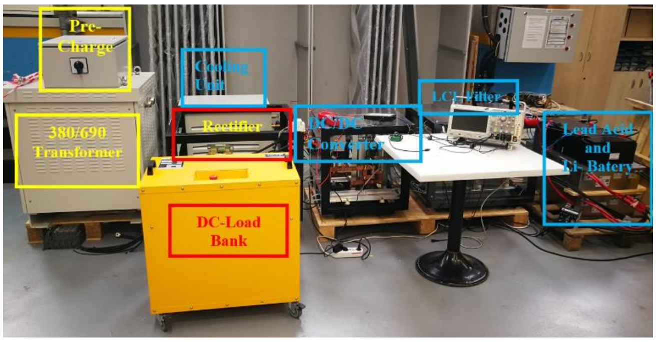

Figure 9 - Proposed DC-DC converter setup

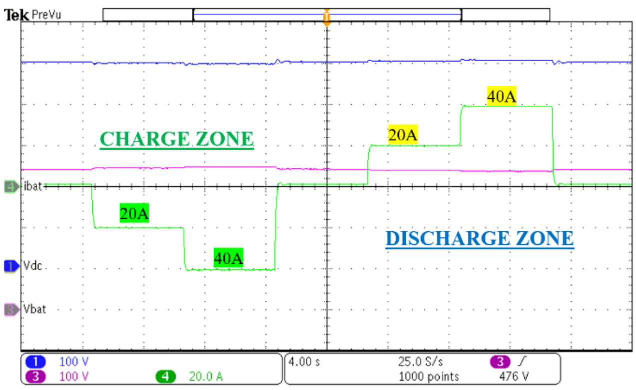

Figure 10 - Proposed DC-DC converter charge/discharge mode results

Table 2 shows the numerical data obtained during the tests, including voltage, current, temperature, and power measurements for both charging and discharging phases. This data serves as quantitative evidence of the proposed topology's performance and effectiveness. It is crucial for ensuring the system's long-term reliability, efficiency, and sustainability. To achieve this goal, the system adheres to stringent charge and discharge parameters, carefully monitors battery temperature, and employs advanced control strategies. The approach to battery health preservation, encompassing carefully controlled charge/discharge parameters, meticulous temperature management, and rigorous testing, ensures that batteries operate within safe limits, extending their lifespan and contributing to the system's overall efficiency and sustainability.

- *Charge Rate:* Limiting the charge rate to 0.5C ensures gentle charging, preventing excessive heat generation and prolonging battery life.
- *Discharge Rate:* Limiting the discharge rate to 1C (or even lower in certain scenarios) protects batteries from deep discharge and extends their lifespan.
- *Charge Voltage:* Maintaining a charge voltage around 4.15V prevents overcharging, which can degrade battery performance.
- *Discharge Voltage:* Keeping the discharge voltage under 3.3V (under load) avoids deep discharge that can damage batteries.
- *Temperature Management:* Ensuring battery temperature remains within an optimal range (ideally around room temperature) is crucial for preserving battery health. Excessive temperatures can accelerate battery degradation, while low temperatures can reduce battery capacity.

Test results in Table 2 demonstrate that the system adheres to the recommended charge/discharge parameters and temperature management guidelines, effectively preserving battery lifespan.

Table 2 - Data obtained from the study profile

Description and Notation							
	Parameter	No Load	Charge-1	Charge-2	Discharge-1	Discharge-2	
1	Vdc_bus	498	495	492.8	500.4	502.4	V
2	Vbat	337	341.3	344	336.3	333.5	V
3	ibat	0	20	40	20	40	A
4	idc	0	16.73	38.51	5.6	12.85	A
5	Ah	0	10.69	10.8	10.8	10.59	Ah
6	kwh	0	0	0	0	0	kWh
7	Vmax	4.007	4.102	4.102	4.001	3.995	V
8	Vmin	4.001	4.005	4.005	3.901	3.951	V
9	Tmax	26	26	27	27	27	°
10	Tmin	26	26	26	27	27	°
11	Tmean	26	26	26.5	27	27	°

3.3. General BESS integration concepts

In terms of marine electrical system integrator of BESS, we would like to make 3 different approaches for BESS

1) BESS integration introduction to an existing vessel as a retrofit

2) Battery addition to an existing BESS application on-board

3) New built vessel electrical design with commercial and future development on energy storage systems.

First of all, as an experienced marine electrical system integrator, the basic requirement that is demanded from marine battery supplier is to get pure power quality without any EMC problems. Because in hybrid electric ships, BESS can behave as both power supplier(discharge) and consumer(charge) roles. Batteries and their BMS should be compatible with PMS modes and drive units on-board. For example, each battery on board if they have specific duties like high energy or high power, there should be dedicated DC/DC Converter in order to build a safe DC voltage level. If the existing drives wouldn't be changed, PMS modes can be updated accordingly. Communication between drives and BMS should be arranged as well either MODBUS or CANBUS or any other future protocols.

3.4. Recommendation for BESS integration

According to Elkon's experience in PMS engineering and BESS integration, it would be beneficial to make a ship's initial design for electrical and mechanical installations in a way that would enable easy integration of future BESS developments. Initial design must be a kind of "DAY-1" design, which is made by considering the load analyzes and BESS load profiles as per designed operational needs. Mechanical and electrical design must be done by considering possible "DAY-2", "DAY-3", "DAY-X" installations. Those installations can be done for following reasons:

- By keeping rated power constant, DAY-2, DAY-3 and DAY-X installations can provide greater DoD
- DAY-2, DAY-3 and DAY-X installations may include new technologies that increases efficiency and safety
- DAY-1, DAY-2, DAY-3 and DAY-X approach can be financially more applicable for ship owners and encourage them to invest more in BESS technologies
- Modular and plug&play solutions will be pre-engineered and be more applicable.

Spaces assigned for possible DAY-2, DAY-3 and DAY-X installations can be used for other purposes (for cargo etc.) during the usage of DAY-1 design.

4. Conclusions

In conclusion, this paper underscores the critical importance of operational strategies in realizing the full potential of onboard battery energy storage systems (BESS) for commercial vessels. The maritime industry, driven by the pressing need for sustainability, is increasingly integrating battery technologies into their operations. However, their successful deployment relies on a complex interplay of factors including optimizing battery lifespan, maximizing efficiency, minimizing operational costs, and ensuring safety and reliability. The strategies must also be adaptable, considering the specific operational profile of each vessel. The paper also brings to focus the significant role that cutting-edge developments such as the DC-DC converter design and the Digital Twin Module play in enhancing battery performance and lifespan. These innovative solutions, coupled with well-planned operational strategies, pave the way for the maritime industry to achieve its sustainability goals while reaping the economic and operational benefits of onboard battery systems.

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References

[1] M. -I. Gerrero-Molina, Y. -A. Vásquez-Suárez and D. -M. Valdés-Mosquera, "Smart, Green, and Sustainable: Unveiling Technological Trajectories in Maritime Port Operations," in IEEE Access, vol. 12, pp. 47713-47723, 2024, doi: 10.1109/ACCESS.2024.3376431.

[2] T. U. Aktas, J. Shi, G. J. Lim, J. Prousalidis, F. D'Agostino and C. Liang, "Decarbonization of the Maritime Transportation Systems: Recent Progress, Challenges, and Prospects," 2023 IEEE Electric Ship Technologies Symposium (ESTS), Alexandria, VA, USA, 2023, pp. 224-230, doi: 10.1109/ESTS56571.2023.10220507.

[3] I. Filippopoulos, X. Christodoulidou and Y. Kiouvrekis, "How Can Shipping Companies Manage Environmentally Beneficial Operations in a Sustainable Way?," 2024 ASU International Conference in Emerging Technologies for Sustainability and Intelligent Systems (ICETSIS), Manama, Bahrain, 2024, pp. 1579-1583, doi: 10.1109/ICETSIS61505.2024.10459657.

[4] D. Kaklis, P. Eirinakis, G. Giannakopoulos, C. Spyropoulos, T. J. Varelas and I. Varlamis, "A big data approach for Fuel Oil Consumption estimation in the maritime industry," 2022 IEEE Eighth International Conference on Big Data Computing Service and Applications (BigDataService), Newark, CA, USA, 2022, pp. 39-47, doi: 10.1109/BigDataService55688.2022.00014.

[5] Y. Yan, D. Gao and H. Jiang, "An Energy Control Strategy in Hybrid Electric Ships Considering the Battery Life," 2023 IEEE 3rd International Conference on Industrial Electronics for Sustainable Energy Systems (IESES), Shanghai, China, 2023, pp. 1-6, doi: 10.1109/IESES53571.2023.10253746.

[6] S. Karimi, M. Zadeh and J. A. Suul, "Shore Charging for Plug-In Battery-Powered Ships: Power System Architecture, infrastructure, and Control," in IEEE Electrification Magazine, vol. 8, no. 3, pp. 47-61, Sept. 2020, doi: 10.1109/MELE.2020.3005699.

[7] M. Akbarzadeh, J. D. Smet and J. Stuyts, "Cost Assessment of Battery Hybrid Energy Storage System for Full-Electric Marine Applications," 2022 22nd International Scientific Conference on Electric Power Engineering (EPE), Kouty nad Desnou, Czech Republic, 2022, pp. 1-6, doi: 10.1109/EPE54603.2022.9814114.

[8] P. S. Sletten and M. Zadeh, "Comparative study of energy efficiency and cost optimization in low-emission marine power systems with alternative fuels," 2022 IEEE Transportation Electrification Conference & Expo (ITEC), Anaheim, CA, USA, 2022, pp. 652-657, doi: 10.1109/ITEC53557.2022.9813749.

[9] E. Erol, C. E. Cansoy, and O. Ö. Aybar, “Assessment of the impact of fouling on vessel energy efficiency by analyzing ship automation data,” Applied Ocean Research, vol. 105, pp. 1–10, 2020. doi: 10.1016/j.apor.2020.102418.

[10] H. Wenzl, “Encyclopedia of Electrochemical Power Sources,” in *BATTERIES AND FUEL CELLS | Lifetime*, 2009, pp. 552-558.

[11] R. Xiong, L. Li, and J. Tian, "Towards a smarter battery management system: A critical review on battery state of health monitoring methods," *Journal of Power Sources*, vol. 405, pp. 18-29, 2018, doi: 10.1016/j.jpowsour.2018.10.019.

[12] W. He et al., “Lessons learned from the commercial exploitation of marine battery energy storage systems,” Journal of Energy Storage, vol. 87, p. 111440, May 2024, doi: 10.1016/j.est.2024.111440.

[13] Ö. Atmaca, E. Erol, T. Kamal and M. Karabacak, "Design of an H-Bridge Bidirectional DC-DC Converter with LCL Filter for High Power Battery Applications," 2019 1st Global Power, Energy and Communication Conference (GPECOM), Nevsehir, Turkey, 2019, pp. 238-241, doi: 10.1109/GPECOM.2019.8778485.

[14] Y. Shi, B. Lei, Y. Zheng, S. Xu and J. Chen, "Design and Control of Battery Energy Storage System Based on Cascaded Multilevel Converter with Reduced Low-Frequency Battery Current Ripple," 2020 IEEE 4th Conference on Energy Internet and Energy System Integration (EI2), Wuhan, China, 2020, pp. 355-360, doi: 10.1109/EI250167.2020.9346910.