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A Multi-Objective Co-Design Optimization Framework for Microgrid Architecture in Marine Application

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***Abstract*—Multi-objective optimization of the battery energy storage system (BESS) microgrid architecture in the marine sector is crucial, considering the immense power demand and multiple possible electrical/electronic topologies. As a result, various steps are often taken to simplify the design problem, limit the size of the design space, and make separate optimizations in different components and converters. However, the first step is to properly size and design the microgrid architecture. This paper proposes a multi-objective co-design optimization framework for the optimal selection of the microgrid and power electronic (PE) architecture in a vessel's BESS. For this purpose, a non-dominated sorting genetic algorithm (NSGA-II) optimization, in addition to the Pareto Search, is used to generate all the possible solutions and then illustrate the optimal points, which enables a trade-off between the total initial cost of PEs and total converter losses as objectives. The cost function that leads to the optimum architecture selection considers capital cost and efficiency objectives. The interoperable framework is applied considering four different DC/AC architectures. Finally, from the objective perspective, the globally best architecture is determined as the framework's output.**

***Index Terms*—optimal sizing, co-design optimization, electrical/electronics (E/E) architectures, marine technology, battery energy storage system (BESS), marine applications, optimization, cost-effectiveness**

I. INTRODUCTION

Efforts to reduce green house gases (GHG) emissions in the shipping industry are crucial due to its significant contribution to global emissions [1]. The international maritime organization (IMO) imposes limitations on vessel emissions under the international convention for the prevention of pollution from ships (MARPOL) treaty to address this issue. To achieve emissions reduction and sustainability, transitioning from fossil fuels and inefficient engines to advanced technologies is essential [2]. Research focuses on enhancing internal combustion engine (ICE)s, exploring hybrid systems and alternative energy sources, and developing integrated power systems for ship electrification. Electric propulsion offers benefits such as lower emissions and efficiency at low speeds, making it ideal for future vessel electrification [3].

The integrated power system (IPS) revolutionizes traditional power systems by integrating all generators into a unified grid to distribute power to consumer systems [4]. This system's power-sharing capability enhances flexibility and reliability, offering economic and environmental benefits such as improved fuel efficiency and reduced GHG emissions. The evolution of marine propulsion systems, culminating in IPS, is evident in Fig. 1. IPS can generate the same power output at low and medium speeds as conventional electric systems while using fewer prime movers. Consequently, energy efficiency has become a pivotal concern in the marine industry [5], [6].

In recent years, significant progress has been made in the design of electrical propulsion systems, with various configurations based on vessel type and technological advancements [7]. The move towards an all-electric ship (AES) concept has led to an increased usage of electrical devices, necessitating crucial power conversion stages [8]. PE converters play a vital role in delivering power to different loads within maritime power systems [9]. These advancements are shaping the maritime industry's future of electrical propulsion and power systems.

The marine industry has traditionally relied on alternating current (AC) systems, but interest in direct current (DC) systems has grown due to advances in PEs, renewable energy, and energy storage system (ESS). Market demands for cleaner and more efficient power, along with environmental regulations, are driving the development of E/E architecture [10]. The availability of off-the-shelf components and the compatibility of DC systems with modern energy sources have led to the development of various DC, AC, and hybrid solutions.

The adoption of ESS on vessels has risen to reduce GHG emissions, but challenges remain for large ESS used in full-electric marine applications. These obstacles include high costs, safety concerns, and thermal management. Marine ESS technologies fall into two categories: high-energy and high-power. While higher energy devices like batteries, fuel cells,

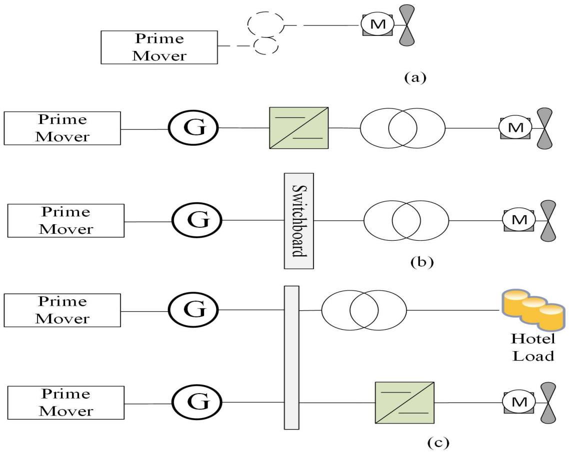

Fig. 1. (a) Mechanical propulsion (b) Conventional electric-drive propulsion (c) IPS [9]

pumped hydro , and compressed air energy storage (CAES) offer long-term energy, they have low power. Conversely, higher-power devices like flywheels, supercapacitors, superconducting magnetic energy storage (SMES), and high-power batteries provide short bursts of high power. Combining higher energy-density with higher power-density devices enhances ESS capabilities [11].

The optimization of BESS design involves various factors such as sizing, grid integration, technical performance, and economic perspective. Optimal sizing of BESS installation is essential for reducing power outages, fuel costs, and committed power generation costs [12]. It has been noted that BESSs face challenges regarding investment costs, emphasizing the significance of appropriate BESS sizing for microgrid design and management. With the increasing use of ESSs in the marine industry, there is a growing need for detailed investigation and optimization of power converters used in vessels, particularly in higher power ranges [13]. This optimization aims to achieve specific economic goals, including maximizing profits and minimizing operational power losses or component costs.

Despite a growing focus on marine IPS optimization, most of the emphasis in such research has been on power generation methods such as renewable energy optimization [14]–[16], lifecycle assessment of fuel cell powered ships [17], [18], and energy storage sizing in all-electric ships [19], [20]. Other studies have also been conducted on optimal energy management from a voyage scheduling perspective [21], [22]. According to the author's best knowledge, operational optimization on converters connected in ship ESS microgrids has yet to be done at high-power scales.

The majority of ongoing Horizon-Europe funded projects, such as NEMOSHIP (GA,No:101096324), FLEXSHIP (GA,No:101095863), iSTORMY (GA,No:963527), etc. [23], aim to develop, test, and demonstrate new innovative technologies, methodologies, and guidelines to expedite large BESS deployment and optimize its utilization by 2030, particularly in hybrid and fully electric ship configurations. This article introduces a problem structure and solution approach for determining the optimal selection of E/E architecture in a vessel battery system using a combination of all Pareto efficient solutions and a quadratic programming algorithm for two objectives: initial PE cost and PE efficiency. Additionally, the NSGA-II algorithm can be utilized to address other multi-objective problems, such as minimizing annual net profits, energy consumption rate, annual energy exchanged with the grid, and battery degradation. Furthermore, it is mentioned that a multi-objective genetic algorithm (MOGA) can be employed for the optimization of nonlinear, nonconvex, discrete, continuous, mixed-integer, and multiple-objective problems. Previous research has also focused on optimizing the size of hybrid battery energy storage system (HBESS) using certain rule-based energy management methods in a general form. This paper first explores methodology and system description. The following section outlines a model configuration for HBESS. Another section is devoted to formulating the problem for co-design optimization, followed by a discussion of variables and constraints. The NSGA-II multi-objective optimization is then discussed, highlighting its priority and benefits within this framework. The third part presents the optimization results and provides a detailed discussion. The research concludes with the final section.

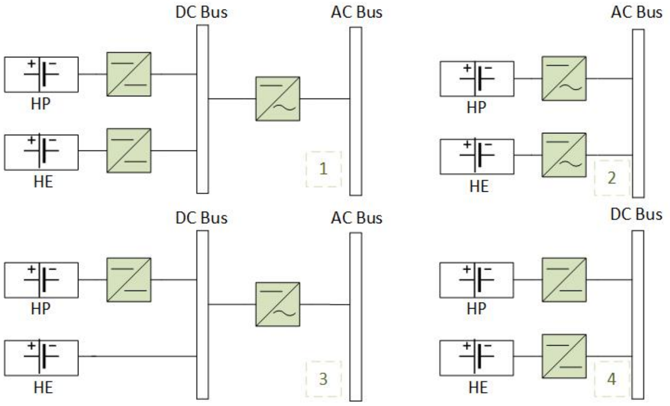

Fig. 2. Different architectures mixing HP and HE storage units.

II. METHODOLOGY AND SYSTEM DESCRIPTION

This study proposes a modular and standardized 1MWh battery energy storage solution designed to leverage diverse storage units and multi-objective optimization, thereby enabling efficient, optimized, and safe utilization, both applicable to hybrid and fully electric ships. The framework of this article is established on data obtained from an operational use case (*Le Commandant Charcot (LCC)*), taking into consideration its power profile, energy demand, and high-power and high-energy battery sets.

A. HBESS Model Configuration

This section presents the system considered for the framework shown in Fig. 2. A synergic design goal with a nominal

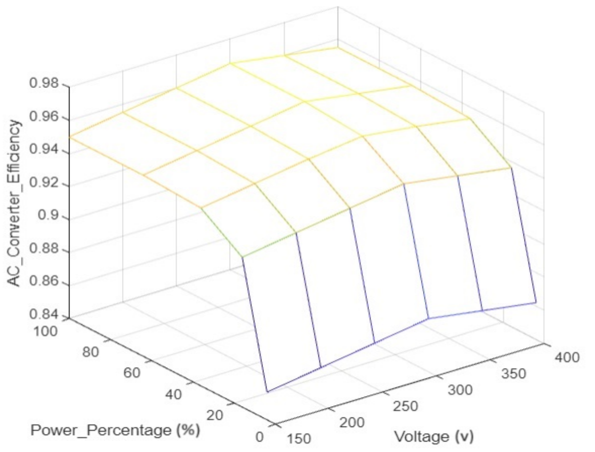

Fig. 3. *Efficiency map used for the converter model.*

power of 1 MW and nominal capacity of 1 MWh HBESS with four different topologies is set in the co-design optimization framework (COF). The COF is applied to the DC side of the system for the hybridization of cell technologies of two independent battery packs, namely battery pack-1 (HE battery pack) and battery pack-2 (HP battery pack), and to the PE interface. The DC-AC converter model is a basic power converter with an efficiency curve sourced from the datasheet. The converter currently employed in the use case is responsible for converting the battery's DC output power into the transformer's AC input. The efficiency map of the module utilized in the model is shown in Fig. 3. Since the simulation framework focuses on energy control, a low-fidelity model in which the output voltage follows the reference input voltage is used for the DC and AC converters. This selection also aligns with the power profile adapted for maximum battery usage values in the use case of LCC (see Fig. 4) and the maximum current discharged by the battery.

The COF is created in a MATLAB/Simulink® modeling environment to depict the behavior of fully coupled HBESS. The framework is designed in a modular way, shown in Fig. 5, comprising an input layer and a programming layer for operational flexibility. The input layer collects user input for design specifications, constraints, and database selection for planned system components and connection topology, followed by selection criteria. The programming layer interfaces the input data and the component model with a specific system model configuration for simulation (with a selected topology) to the final output with an iterative optimization routine and decision-making criterion. The optimization routine integrates a co-design method with multi-objective features and an evolutionary optimizer to identify the Pareto front or feasible solution that meets all the constraints and requirements of the HBESS-related PE design [24]. Both battery packs are connected to the grid using all considered architecture topologies, as shown in Fig. 2. The core tasks of the COF are summarized as follows:

- Illustrating a trade-off between component initial cost and efficiency to identify the best configuration.
- Sizing PEs in terms of rating and number of modules in a specific topology.
- Finding the global optimal solution for PE architecture from the selected topologies.

B. Co-Design Optimization Problem Formulation

This section first formulates the co-design framework and presents the optimization problem. Then, the objective functions are described. The co-design optimization problem for the PE converter can be formulated as equation (1) with a control plant. The control plant ensures the power-sharing between two battery packs in the function of their C-rate and SoC to meet the use case power profile.

$$\begin{gathered}\min_{x\in(d_s,d_c)} \quad F(x) = [f_1(x), f_2(x)] \\ \text{Subject to } g_i(x) \le 0 \\ X = \{x \mid g_m(x) \le 0, m = 1, 2, 3, ..., M\} \\ S = \{F(x \mid x \in X\}\end{gathered} \tag{1}$$

In this equation, x stands for the design variables, which consist of control plant variables (*dc*) and system variables (*ds*). *gi(x)* represents the vector of inequality constraints for control plant and system variables, and *m* is the total number of inequality constraints. *X* represents the feasible decision space, and *S* represents the criterion space [25]. The framework takes into account the capital costs of the converters to ensure economically optimal solutions, as depicted in equation (2):

$$\begin{aligned}Cost = &\sum_{i=1}^{n}(N_{ac-pe} * C_{ac-module}) \\ &+ \sum_{j=1}^{m}(N_{dc-pe} * C_{dc-module}) \\ &f_1(x) = Cost\end{aligned} \tag{2}$$

where n and m are the numbers of AC and DC converters, respectively, N represents the number of sub-modules, and C stands for the price of each AC and DC module. The system efficiency in this framework includes the efficiency of the converters used, and it has been considered to assess the economic viability of PE converters. Equation (3) illustrates the formulation of the efficiency as an objective:

$$\begin{aligned}P_{Total} &= P_{Nominal} \\ P_{Loss}^{pu} &= \frac{\sum_{i=1}^{k} P_{Loss}}{P_{Nominal}} \\ \eta &= 1 - P_{Loss}^{pu} \\ f_2(x) &= \frac{1}{\eta}\end{aligned} \tag{3}$$

where P_{Total} and $P_{Nominal}$ are the total output electric power and nominal power of the components, respectively. The total number of converters is denoted by k, and η represents the conversion efficiency.

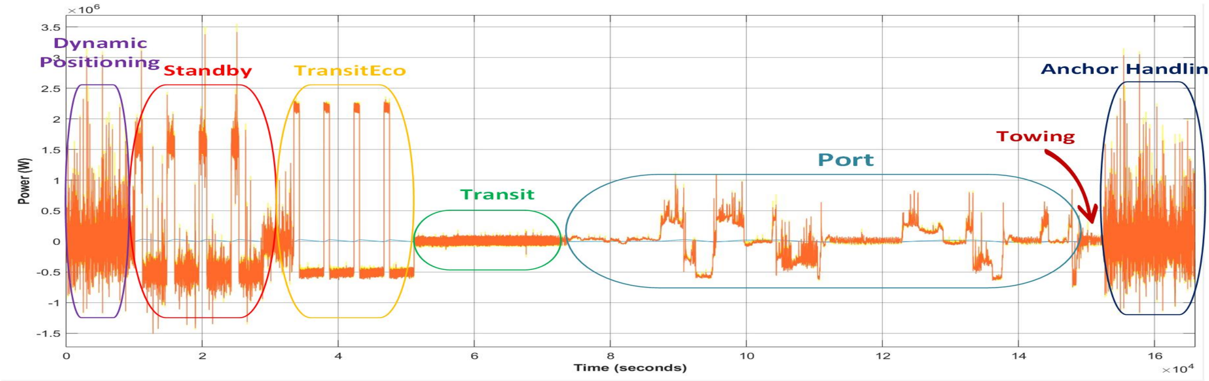

Fig. 4. Power profile with maximum battery usage.

C. Variables and Constraints

The constraints define conditions for variables that must be met when designing system components. In this paper, the quantity of each PE module is treated as a variable, with explicit constraints set between $1 \rightleftharpoons 50$, where the nominal power for each module is $20kW$.

D. NSGA-II Multi-Objective Optimization

A genetic algorithm was chosen for its capability to implement various control algorithms and component models without requiring adjustments to the optimization framework. Fig. 5 illustrates the schematic of the global method developed. In the assessment of each microgrid configuration, the simulation provides metrics for capital cost, while energy efficiency analysis offers the performance indicator [26]. The NSGA-II algorithm is employed, with its specific settings detailed in table (I). This genetic algorithm allows for obtaining the non-dominant Pareto frontier of the objectives. Its advantage lies in efficiently exploring the search space. The algorithm initializes with an initial population of a predefined size, each individual of which is then evaluated through simulation and reliability analysis. Following this, the population is ranked based on two indicators; cost and efficiency. Subsequently, the algorithm employs selection, crossover, and mutation to generate a new child population. The parent population and the children are combined and ranked to select individuals for the new generation. This iterative process continues until the termination criteria are met. The selection technique includes elitism, ensuring that non-dominated individuals from the combined parent and the child populations proceed to the next generation [27].

III. OPTIMIZATION RESULTS AND DISCUSSION

In this part, the co-design optimization results are presented. The simulated microgrid, which represents the four configurations depicted in Fig. 2, is analyzed utilizing the NSGA-II optimization algorithm for a 2-day power profile. As the desired power profile spans a wide range of the ship's operating modes (refer to Fig. 4), the 48-hour duration is repeated throughout the optimization process, which makes it

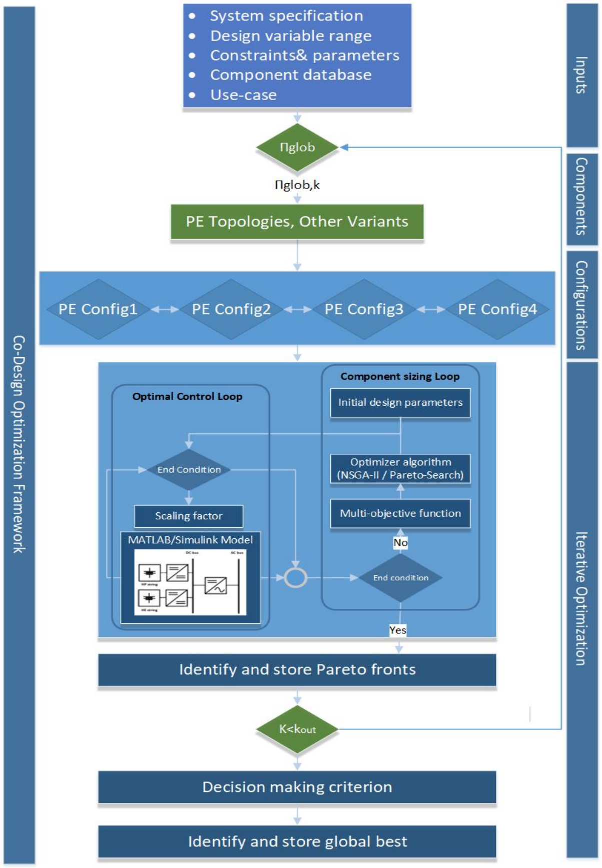

Fig. 5. Optimization framework flowchart.

TABLE I
NSGA-II SETTINGS.

Population size	300
Number of generations	10
Crossover	simulated binary
Mutation	Gaussian distribution
Stall generation limit	5
Tolerance	$1e^{-}4$
Stop criteria	Max number of generations

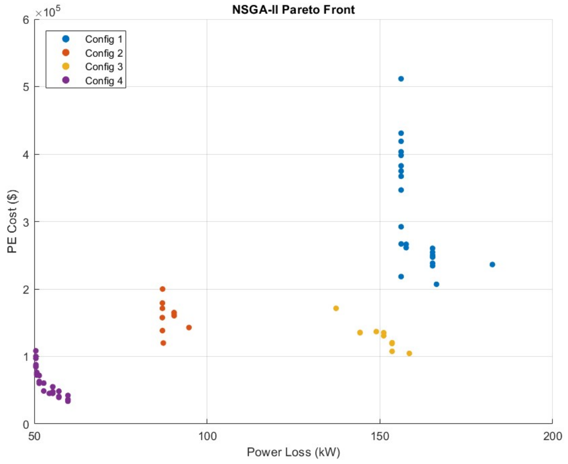

Fig. 6. NSGA-II optimal solutions found by optimization framework.

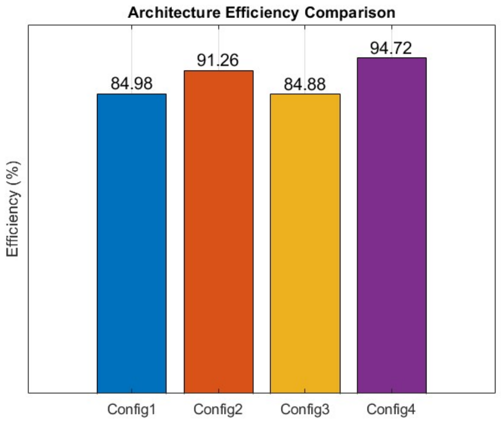

Fig. 7. Normalized values of system efficiency in four selected architectures.

highly time-consuming. The number of generations is limited to address this issue, and the optimization is iterated for ten generations. As a result, several possible solutions for each configuration can be found in Fig. 6. While a single trend line is not apparent, it is evident that solutions associated with configuration four, representing the DC microgrid, have the lowest cost and the lowest total power losses.

The number of modules in each converter unit is a decision variable. Each converter initially consists of several 20kW modules that, together, will form a 1MW microgrid. Different combinations of the number of modules enable the microgrid to operate in an optimal design, which means it will require the lowest number of modules while achieving the highest efficiency. NSGA-II, due to its capabilities, tried various module combinations for each converter to achieve the optimum possible solutions. The range of decision variables for all architectures is shown in Fig. 8. Using the optimization results and equation (3), Fig. 7 compares the efficiency of the four target architectures. Considering the optimum points for each architecture, It can be observed that the fourth configuration achieves the highest efficiency, followed by the second configuration, and the first one has the lowest efficiency rate.

IV. CONCLUSION

The study results demonstrate that when considering the decision variables described, the DC microgrid offers higher efficiency and greater cost-effectiveness. However, achieving the optimal solution requires balancing the trade-off between objectives, capital cost, and converter efficiency.

The results also suggest that DC microgrids are superior in eco-mobility and sustainability due to minimum energy loss. Therefore, it is important to explore the long-term benefits of investing in maritime DC microgrids and their potential impact on energy market dynamics.

Other significant variables that should be addressed in future research include battery sizing, total cost of ownership (TCO), lifetime, safety, and reliability.

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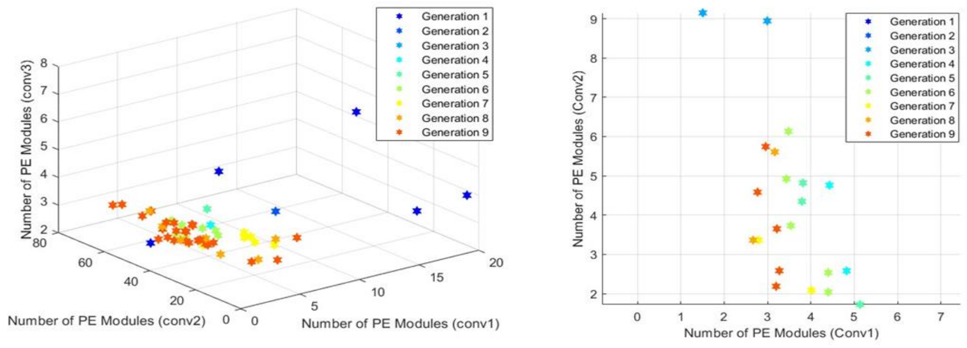
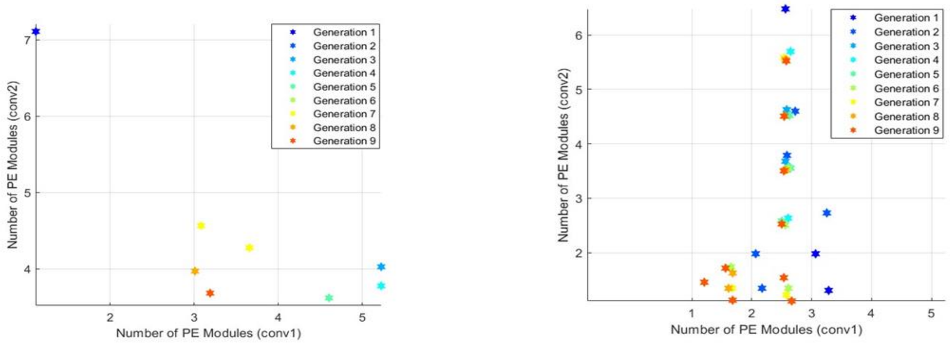


(a) Configuration 1

(b) Configuration 2



(c) Configuration 3

(d) Configuration 4

Fig. 8. Population evolution of decision variables: Number of PE modules in each converter.

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