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Optimal Sizing of Hybrid Battery-Supercapacitor -Generator System in Electric Ship using Genetic Algorithm

Chanraksa Sorn[1], Vita Lystianingrum [1*], Agoes Santoso [2]
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***Abstract*— The fossil fuel emissions from the ship have significant impacts on climate change, environmental quality, and human health. The marine sector has consequently grown increasingly interested in implementing greener and more sustainable energy solutions. The electric propulsion ship is powered by hybrid energy storage has the ability to lower emissions, improve the power quality, and lower fuel consumption. In this study, the combine of battery and supercapacitor are chosen as a hybrid energy storage system to supply power to the electric ship and diesel generator is an additional power source. The main objective is to sizing the hybrid energy storage system to minimize the total cost while maintaining reliable energy supply. The optimal sizing of each component is conducted in MATLAB using Genetic Algorithm. The result indicates that the optimal power rated of P_{bat} is 100 kW and P_{sc} is 301.19 kW, while the optimal capacities rated of E_{bat} is 121.27 kWh and E_{sc} is 109.86 kWh. Over a 20-year period, the total of this project is $ 1,390,422.**

Keywords— Hybrid Energy Storage System (HESS), Battery, Supercapacitor (SC), Diesel Generator (DG), Genetic Algorithm (GA)

NOMENCLATURE

a_{b1}	Power cost coefficient of battery ($/kW)
a_{c1}	Power cost coefficient of SC ($/kW)
a_{b2}	Cost factor of battery ($/kWh)
a_{c2}	Cost factor of SC ($/kWh)
P_{bat}	Rated power of battery (kW)
P_{sc}	Rated power of SC (kW)
E_{bat}	Rated energy of battery (kWh)
E_{sc}	Rated energy of SC (kWh)
$P_{bat(i)}$	Power allocation of battery (kW)
$P_{sc(i)}$	Power allocation of SC (kW)
$P_{dg(i)}$	Power allocation of DG (kW)
$P_{L(i)}$	Power of load demand over time step (kW)
$C_{o,bat}$	Cost factor O&M of battery ($/kWh/y)
$C_{o,sc}$	Cost factor O&M of SC ($/kWh/y)
L	Life time of the project (years)
r	Discount rate (%)
L_{bat}	Life time of battery (cycles)
L_{sc}	Life time of SC (years)
$N_{rep,bat}$	Number of batteries that need to be replaced
$N_{rep,sc}$	Number of SC that need to be replaced
$C_{in,bat}$	The installation cost of battery ($/kW)
$C_{in,sc}$	The installation cost of SC ($/kW)
$C_{rep,bat}$	The replacement cost of battery ($/kW)
$C_{rep,sc}$	The replacement cost of SC ($/kW)
$C_{o\&m,bat}$	The O&M cost of battery ($/kW)
$C_{o\&m,sc}$	The O&M cost of SC ($/kW)
C_{in}	Cost required to purchase of HESS ($)
$C_{op\&m}$	Cost O&M of HESS ($)
C_{rep}	Cost replacement of HESS ($)
C_{total}	Total cost of HESS in this project ($)
SOC_{bat}	State Of Charge of battery (%)
SOC_{sc}	State Of Charge of SC (%)
$\Delta P_{b,max}$	Power rate of change of battery (kW/s)

I. INTRODUCTION

Nowadays, fossil fuels are used by ships and other contemporary modes of transportation. Their emissions have a major influence on human health, environmental pollution, and the climate issue. The State of Shipping and Oceans Report states that compared to most other modes of transportation, maritime transportation produces fewer greenhouse gases (GHG) per ton-kilometer. Additionally, more than one billion tons of carbon dioxide equivalent (CO_2e) are released annually by marine shipping as carbon dioxide (CO_2), methane, black carbon, and other climate pollution [1]. In order to enhance the ships' environmental conditions and address the growing emissions scenario. The use of HESS and DG applications on electric ships is the subject of the researcher's investigation. The integrated aims to support sustainable maritime operations and improve energy efficiency [2].

The electric propulsion ship is powered entirely by the electricity from batteries or fuel cells and use electric motor for propulsion [3]. Moreover, the ship's hybrid energy storage technology and electric propulsion make it environmentally friendly, zero greenhouse gas emission while operating, improve power quality and lower fuel consumption [4]. A system that combines two or more storage system technologies with somewhat complementary qualities is called a hybrid energy storage system. Energy storage devices come in a variety of forms, including fuel cells, flywheels, batteries, supercapacitors, and pumped hydro storage (PHS) [5, 6].

Chanraksa Sorn, Vita Lystianingrum, Department of Electrical Engineering, Sepuluh Nopember Institute of Technology, Surabaya, 60111, Indonesia. E-mail: vita@ee.its.ac.id

Agoes Santoso, Department of Marine Engineering, Sepuluh Nopember Institute of Technology, Surabaya, 60111, Indonesia.
E-mail: agoes@its.ac.id

Technologies for energy storage systems fall into two categories: energy density and power density. The former, such as flywheels, supercapacitors, and superconductors, have the drawbacks of low energy density but the benefits of greater power density and quick response times [7, 8].

High energy density is advantages for batteries and pumped hydro storage, but poor power density and lagging reaction speed are disadvantages. This limits variety of potential applications since it is challenging for one energy storage system to achieve both high power and high energy density simultaneously. Additionally, in order to ensure technological complementarity, two or more types of energy storage system must be integrated to form a hybrid energy storage system (HESS) [9, 10].

There are many applications using HESS for supplying the power demand such as renewable energy. For PV system, to design and test energy management system that uses a neural network to control how energy is shared between battery and SC. There were combining of the battery (good for long term storage and SC (good for fast power bursts), the system aims to minimize battery stress and prolong its life [11]. For marine applications powered by energy storage devices provide a huge of advantages. One significant benefit is their capacity to increase the mechanism system stability by making up for internal combustion engines slower reaction to load demands, which enhances vessel control and security [12]. Furthermore, by optimizing fuel use and lowering engine maintenance, HESS can save operating expenses. They serve as an extra power reserve, enhancing the power system's redundancy and helping it with frequency, voltage fluctuation, load leveling, and power quality [13].

A large number of previous researchers [14] have used various types of optimal solutions with different purposes. By design hybrid energy storage system in electric ship, to creating a two-layer optimization problem, the researcher is able to solve the issue of determining the ideal energy storage size. The inner layer determines the best power generation scheduling for energy storage capacity, while the outer layer examines all design storage capacities and takes the maximum savings minus cost into account. The outcome is heavily influenced by the parameters of the generating fuel consumption and load profile, particularly the transitory inefficient penalty factor.

There are many methods for solving the optimization problems such as Genetic Algorithm (GA), Dynamic Programming (DP), Mixed Integer Linear Programming (MILP), and Particle Swarm Optimization (PSO), each with its advantages [15]. While GA is widely used and have many advantages, consequently the researcher decides to use GA as a method to address the optimization problem in this research. GA is notable for the flexibility and capacity to guide clear of local minima in very nonlinear search spaces. The genetic algorithm (GA) is a search method that follows biological evolution process to solve any type of optimization problem. It creates an initial set of values for the parameters to be optimized, if not given. After each iteration (generation), it generates a set of values (population) of the variables (individuals) depending on the population in the previous generation. The best value among those acts as parents to generate next set of values and this continues till the optimum solution is achieved based on the solver stopping criteria [16].

According to researcher [17], while energy storage devices provide a workable option for controlling power grid fluctuations brought on by sudden fluctuations in load, finding the ideal balance between cost and value is still a challenging works. In order to resolve this issue, the research suggested a multi-objective optimization model of the ship power grid's energy storage device capacity configuration, using the NSGA-II algorithm as the basis for the decision-making process, the MATLAB software for the simulation, and energy storage system cost, life loss, and stabilization effect as objective functions, as well as the ship power grid's instantaneous power balance and energy storage device charging and discharging as constraint conditions.

Moreover, through the creation of the hybrid energy storage another research [18] suggests an adaptive multi-objective joint optimization framework to address the nonlinear maritime hybrid energy storage system design challenges with complicated operating scenarios, taking into account the energy management system to get the desired outcomes. While collaborative optimization provides the best energy management system solutions for HESS design, multi-objective optimization provides the capacity configuration schemes with the lowest investment cost and minimal degradation of batteries. The non-dominated sorting genetic algorithm-II (NSGA-II), an effective evolutionary algorithm for resolving complex problems with nonlinear and multiple constraints, uses crowding distance calculation, elite reserve strategy, and chosen mechanism to solve the multi-objective optimization problem.

In more recent study [19], to address the critical issue of controlling wind power fluctuations, the authors proposed methods to find the sizing and controlling of hybrid energy storage system. The HESS is composed of battery and SC. The authors recommended a two-part energy management strategy (EMS) along with a combined approach using Parallel Particle Swarm Optimization and Genetic Algorithm (PPSO-GA) after noticing that using just one type of energy storage wasn't enough to handle both high energy and high-power needs. The first energy management system (EMS) level uses spectral analysis to establish the necessary output power that fulfills grid ramp rate constraints, while the second EMS divides power between the battery and the supercapacitor depending on frequency content to minimize battery degradation. The results of simulation indicated that the proposed method is reducing total cost and extending battery lifespan.

The purpose of this research is optimal sizing the hybrid energy storage system to minimizing the total cost of electric ship. A battery and supercapacitor were integrated to form of hybrid energy storage system designed to support the power requirements of the electric vessel. The main power sources are battery and supercapacitor, while the DG is just an additional power source to help the battery and will provide the power available during operation time. GA is used to solve the optimal problem.

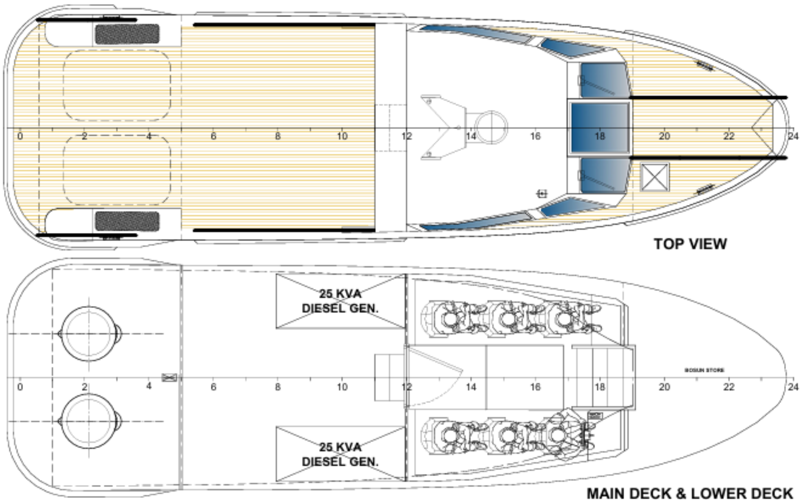

Figure. 1. Model of the Electric Ship

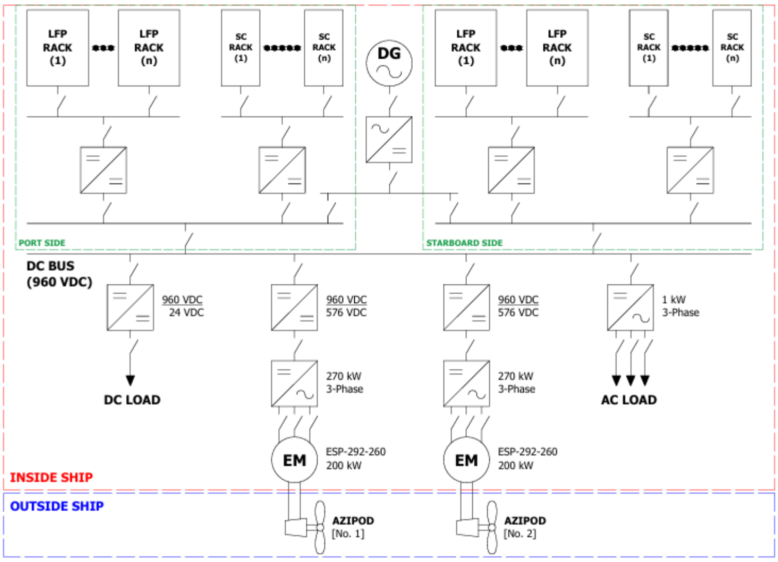

Figure. 2. Configuration of Proposed System

The structure of this paper is described as follows. Section I presents about the introduction. Section II describes the system under study (load profile of the electric ship and configuration of system) and the formulation of optimization problem (objective function and constraints). For the simulation results and discussion are described in Section III. Lastly, the conclusion is povided in Section IV.

II. METHOD

A. System Under Study

The ship under study is an offshore supply vessel used for the transportation. There are two people is crews member and four people is passengers inside the electric ship shown in **Figure 1**. The ship will operate for 5000 seconds (for departure trip, cargo loading and unloading, and arrival trip) during one trip cycle. The more detail about ship can be found in the reference [20]. There will be no charging process during the ship operation and the battery and SC are fully charged before the operation. The principles dimension of the electric ship is described as follows:

L.O. A	= 11.49m
L.W.L	= 9.56m
L.P.P	= 9.96m
B(max)	= 3.78m
H	= 1.75m
T	= 0.8m
Vs(max)	= 30 knots
Power	= 2*200 kW
Endurance	= 300NM
Cargo Area	= 10 m^2

In this electric ship, the AC loads only used for air conditioning and some navigational equipment that requires AC power supplies. The DC loads such as electric propulsion and some navigational equipment will be supplied by DC power. List of loads in the electric ship described as follows:

- Navigational Equipment
- Navigation lamp
- Safety Communication Equipment
- Accommodation Lamp
- Outside lamp
- Air Conditioning
- Horn and Wiper
- Electric Motors for Propulsion (Main load)
- Fuel Transfer Pump 1 phase (There will be used for AC supply)

The configuration of the electric ship power system is shown in **Figure 2**. The hybrid energy storage technology is the main power source and composed of battery and supercapacitor. The bidirectional DC-DC converter enables two-way energy transfer between the hybrid energy storage system and the DC bus, then supply power to ship's electrical loads. The diesel generator (DG) is just an additional power source to help the battery and will provide the power available during operation time. The ship's load profile is appeared in the **Figure 3**. The maximum demand of the propulsion loads is 352 kW [20].

B. Hybrid Energy Storage System (HESS)

1. Battery

Battery is the storage device that store chemical energy and convert the chemical energy to electrical energy. The advantage features of battery such as high energy density, minimal self-discharge and extended lifespan [16].

In this research, ($LiFePO_4$ or LFP) battery is a type of battery that have chosen to be the energy storage system to supply power to the ship loads. The battery utilizes the highly safe lithium iron phosphate (LFP) chemistry. Its safety level is comparable to that of traditional lead-acid batteries and significantly exceeds that of conventional lithium-ion (Li-ion) technologies commonly used by other marine battery manufacturers. Furthermore, LFP offers superior cycle life and a wider operational temperature range compared to Li-ion batteries.

The battery also features a relatively low weight and compact volume per kilowatt-hour of stored energy [21].

2. Supercapacitor

Supercapacitors are the preferred technology for high power applications and low energy applications because of their longer operating lifetime, low maintenance requirements, and superior cold weather performance when compared to batteries [22].

The 2.7V 600F supercapacitor cell was chosen as the type of SC and has the greatest energy content among of the Maxwell's medium cell family and is designed for performance and system optimization in a long life and small form factor. Whether it deployed independently, as part of a modular assembly, or within a hybrid system, Maxwell's supercapacitor products contribute to lowering overall system cost and size, while enhancing the customer's return on investment [23].

3. Diesel Generator

Diesel generator is the essential component of the electric ship power generation system. The purpose of DG is converts the chemical energy that stored in diesel fuel to electrical energy to supply to power propulsion systems and shipboard loads. In this research, DG is just an additional source, support or back up the energy storage system in when the battery state of charge is low or depleted. The power of DG is 50 kW, according to the specification [24] of the DG:

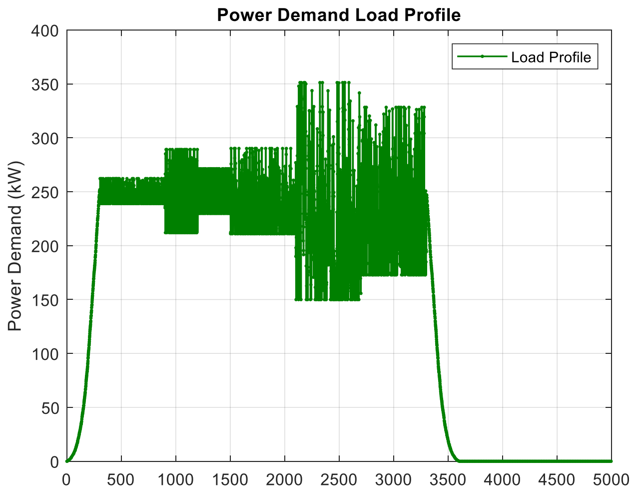

Figure. 3. Power Demand Load Profile of the Ship [20]

- Fuel rate is 4.1 gallons per hour (gal/h)
- Diesel fuel is 0.86 $ per liter ($/L)
- 1.0 $ = 3.785 lite per gallons (L/gal)

Therefore, the diesel fuel ($/gal) will be defined by:

$$diesel\ fuel = 0.86 \times 3.785 = 3.26\ \$/gal \quad (1)$$

Thus, the fuel cost will be multiplied the fuel rate by the diesel fuel is defined by:

$$fuel\ cost = 4.1 \times 3.26 = 13.37\ \$/h$$

C. Optimization Problem Formulation

In the optimization, control variable or decision variable are the parameters that can be adjusted or controlled by the optimization process to get the best results. The control variables are subjected to objective function or constraints to minimize the cost. In this study, there is no charging process during ship's operation. The battery and SC are fully charged before voyage and they have no external recharging sources available while in operation, therefore they are entirely responsible for providing the necessary power for the duration of the mission.

In this paper the control variable that require for the optimization of the cost of HESS could conclude such as:

$$variable = (P_{bat}, E_{bat}, P_{sc}, E_{sc}, P_{bat(i)}, P_{sc(i)}, P_{dg(i)})$$

D. Objective Function

The real valued function whose value is to be either maximized or minimized over the set of possible alternatives is the objective function in a mathematical optimization problem. In this paper, the goal of this research is to reduce the hybrid energy storage system's (HESS) overall cost. The objective function of this research is defined by:

$$\min(C_{total}) = C_{in} + C_{op\&m} + C_{rep} \quad (3)$$

The overall cost of HESS is calculated as the sum of the installation cost, the operation and maintenance (O&M) costs and the last is the replacement costs. The installation cost of the HESS, which is the installation cost that sum by the battery system and the supercapacitor system is defined by:

$$C_{in} = a_{b1}P_{bat} + a_{b2}E_{bat} + a_{c1}P_{sc} + a_{c2}E_{sc} \quad (4)$$

The operation and maintenance cost are calculated as the sum of operation and maintenance (O&M) cost of battery and supercapacitor. In this paper, considering life time of the project is 20 years. The formula is defined by:

$$C_{op\&m} = C_{op\&m,bat} + C_{op\&m,sc} \quad (5)$$

$$C_{op\&m,bat} = C_{o,bat} \times E_{bat} \times \frac{(1+r)^L - 1}{L(1+r)^L} \quad (6)$$

$$C_{op\&m,sc} = C_{o,sc} \times E_{sc} \times \frac{(1+r)^L - 1}{L(1+r)^L} \quad (7)$$

The replacement cost of HESS is calculated as the sum of the replacement cost of battery and the replacement cost of supercapacitor can be defined by:

$$C_{rep} = C_{rep,bat} + C_{rep,sc} \quad (8)$$

$$C_{rep,bat} = \sum_{n=1}^{N_{rep,bat}} \frac{C_{in,bat}}{(1+r)^{L_{bat}}} \quad (9)$$

$$C_{rep,sc} = \sum_{n=1}^{N_{rep,sc}} \frac{C_{in,sc}}{(1+r)^{L_{sc}}} \quad (10)$$

For replacement number of the battery and SC can be defined by the formulation:

$$N_{rep,bat} = \frac{L}{L_{bat}} - 1 \quad (11)$$

$$N_{rep,sc} = \frac{L}{L_{sc}} - 1 \quad (12$$

E. Constraints

In real-life scenarios, design variables are subject to specific limitations, preventing them from being freely chosen. These limitations referred to the design of the constraints, are vital for ensuring both system safety and operational reliability. In this paper the constraints of the optimization are power balance constraints, HESS constraints (energy constraint and power rating limit). The constraints are described as following:

a. Power balance constraint

The power of batteries system and SC system in HESS will directly affect the power balance of the entire ship at any time. Thus, during the operation of energy storage system, the generator power and the power released by the energy storage system should be balanced with the power of ship load. The power balance is defined by:

$$P_{L,i} = P_{bat,i} + P_{sc,i} + P_{dg,i} \quad (13)$$

b. Energy constraint

To ensure the stable operation of the electric ship, the HESS must continuously meet the energy demand. Consequently, the energy stored in both the battery and the supercapacitor must exceed the maximum energy required by the load during operation Since there is not charging during the operation, so the discharge of energy constraints is defined by [18]:

$$E_{bat,rate} \geq \frac{\frac{maxE(i)}{\eta_{dis}\eta_{inv}}}{SOC_{bat,max} - SOC_{bat,min}} \quad (14)$$

$$E_{sc,rate} \geq \frac{\frac{maxE(i)}{\eta_{dis}\eta_{inv}}}{SOC_{sc,max} - SOC_{sc,min}} \quad (15)$$

In the formulation: we assume that the efficiency of discharge (η_{dis}) and inverter (η_{inv}) is 100%.

c. Power rating limit

The power rating limit constraint of the battery and supercapacitor power every time step ensuring the battery and supercapacitor should not deliver more power than it is rated or absorb more power than it can handle. The formulation of constraints is defined by:

$$-P_{bat,rate} \leq P_{bat(i)} \leq P_{bat,rate} \quad (16)$$

$$-P_{sc,rate} \leq P_{sc(i)} \leq P_{sc,rate} \quad (17)$$

The power change rate of a battery, also known as the rate of change (RoC) of battery power, refers to how quickly the battery's output power changes over time. It is mathematically expressed as the absolute difference between the battery's power at two consecutive time steps. Based on specification of battery [21]: $E = 10\ kWh, I = 105\ A\ and\ V = 96\ V, then: \Delta P_{bat,max} = 10.08\ kW/s$

$$|P_{bat}(i+1) - P_{bat}(i)| \leq \Delta P_{bat,max} \quad (18)$$

The function of battery is to handle the slower and steady state demand and the supercapacitor is to handle the fast transient and peak load. When the ship is high power demand, the researcher forces SC should be more active while the battery just handle the normal load. Assume that $P_{threshold} = 250\ kW$, thus the constraints during high load is defined by:

When

$$P_{load}(i) > P_{threshold} \quad (19)$$

$$\Rightarrow P_{sc}(i) \geq P_{bat}(i) \quad (20)$$

However, during normal of operation the battery and supercapacitor is work together to supply power to the electric ship load. The formula is defined by:

When

$$P_{load}(i) < P_{threshold} \quad (21)$$

$$\Rightarrow P_{sc}(i) \leq P_{bat}(i) \quad (23)$$

Table 1 is shown the data value of HESS that to be used in this proposed study. The table's data is originated from [25]. This paper studies the overall cost of the HESS that combines of the battery and supercapacitor during 20 year periods of operation.

TABLE 1.
DATA VALUE OF THIS PROPOSED STUDY [25]

Parameter	Value	Unit
a_{b1}	1200	$/kW
a_{b2}	600	$/kWh
a_{c1}	300	$/kW
a_{c2}	2000	$/kWh
$C_{o,bat}$	19.77	$/kWh/year
$C_{o,sc}$	10	$/kWh/year
$[SOC_{bat,min} and\ SOC_{bat,max}]$	20 and 80	%
$[SOC_{sc,min} and\ SOC_{sc,max}]$	10 and 90	%
L	20	years
L_{bat}	2640	cycles
L_{sc}	5	years

E. Power Sharing Strategy

Due to its simplicity, stability and the rule-based power sharing approach is frequently used in the energy management of electric ship systems. To meet the electric ship power need, this study's rule-based approach combines the use of a diesel generator, battery, and supercapacitor. Generally, the energy managements rule-based uses a collection of parameters and rules that describe the status of the system to decide how power should be allocated. These guidelines are often developed by combining mathematical models, data from experiments, and engineering knowledge. Effective real-time operation, little processing cost, and the lacks of needed condition task for sailing considered as the benefits for this category [13]. So, the power sharing is described as following:

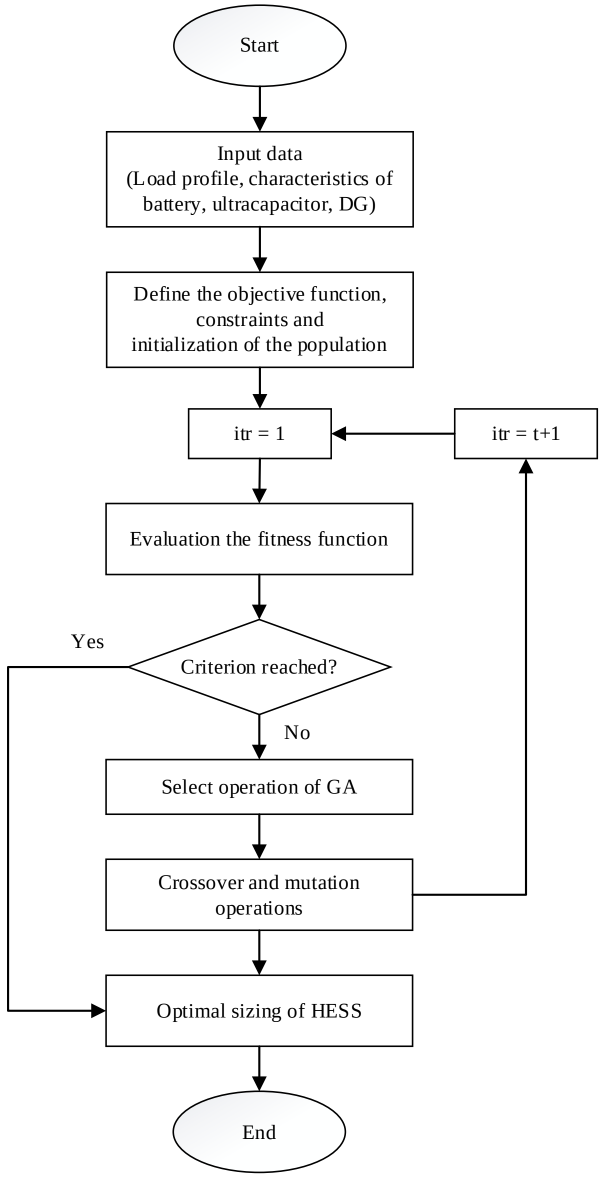

Figure. 4. Optimization Flowchart of GA

During normal operation, the ESS at right side will used as the main source of electricity to the electric motor for propulsion. After certain times, the ESS at right side will be depleted (25% of SOC), so the ship electrical system needs to change the source from the right side to the left side, that is already fully charged. Then the DG is just an additional source to help support the power to the loads in the ship, not storage charging.

F. Optimization Flowchart using GA

The GA is a metaheuristic optimization algorithm, inspired by Charles Darwin's theory of natural evolution. The GA uses three main operators called selection, crossover and mutation. GA searches using a population of solutions as opposed to a single solution. This significantly contributes to GA's resilience. It helps prevent local stationary points and increases the likelihood of attaining the global optimum. Mutation is another GA operator that helps make algorithms more unpredictable, prevents algorithms from becoming stuck at the local optimal point, and improves accuracy and efficiency [26]. The flowchart in **Figure 4** of optimization process is described as following:

Step 1: input the data of ship load profile, data of battery, data of SC and DG.
Step 2: input the objective function and constraints then set the number population and generation.
Step 3: evaluate the fitness function and then check the stopping criterion if the condition meets the number iterations.
Step 4: if yes, calculate the optimization problems using Genetic Algorithm and see the result of battery and SC rating and also the result of battery, SC and DG every time step.
Step 5: if no, select operation of GA then select crossover and mutation operations
Step 6: if the condition is satisfied, the result optimization has found.

III. RESULTS AND DISCUSSIONS

In this chapter, the author will discuss about the result of hybrid energy storage system (HESS) optimization using GA in MATLAB. The results include the optimal power and energy rating of battery and supercapacitor, the energy rating of battery and supercapacitor and the associated system cost. **Table 2** have shown that the result of HESS in this proposed study using GA optimization in MATLAB simulation.

The rated value optimization of battery and supercapacitor are 100 kW and 301.19 kW, indicating that the SC is designated to handle high power, short duration transients, while the battery is sized for base-load or slower dynamics. Assigning specific roles to each component follows standard practices in HESS design, where the battery handles longer duration energy needs and the supercapacitor deals with sudden power demands. In this case, the optimized energy capacities were determined to be 121.27 kWh for the battery and 109.86 kWh for the supercapacitor. This amount of number insurance that there are enough energy capacities for the battery and supercapacitor without depletion or experiencing frequent cycling. The battery has high energy rating that could support sustained energy supply, while the capacity of SC is suitable for power fluctuations. Additionally, the installation cost of the HESS is $ 502,839, the operation and maintenance costs at $ 108, the replacement cost is $ 887,474 and the total cost of this project is $ 1,390,422.

In **Figure 4**, the graph illustrates the power distributions of a hybrid energy storage system comprising a battery, supercapacitor and diesel generator is response to the load dynamic over simulation period. The diesel generator (red curve) operates at a constant power source of 50kW throughout the active period, indicating its use as a base power source to maximize fuel efficiency. While T = 100s to T = 2200s the blue curve shown that the battery supplements the power by contributing between 50 kW to 100 kW during periods of stable and low load demand.

TABLE 2.
HESS RESULTS OPTIMIZATION USING GA IN MATLAB SIMULATION

Parameter	Value	Unit
P_{bat_rated}	100	kW
E_{bat_rated}	121.27	kWh
P_{sc_rated}	301.19	kW
E_{sc_rated}	109.86	kWh
$C_{bat\&sc\_installation}$	502,839	$
$C_{bat\&sc\_op\&m}$	108	$
$C_{bat\&sc\_replacement}$	887,474	$
$Total\ cost$	1,390,422	$

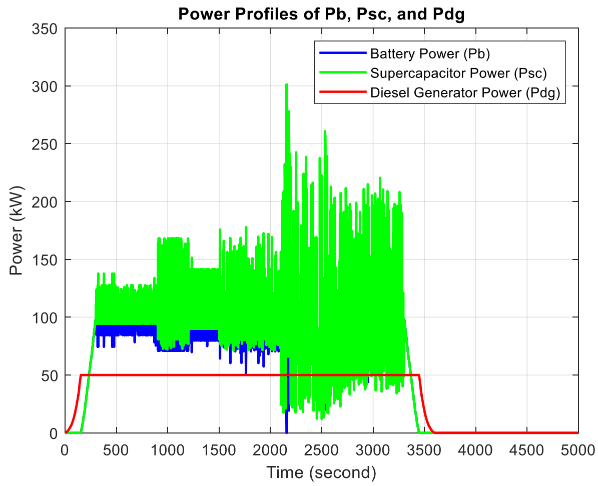

Figure. 4. Power Profiles of Pb(i), Psc(i) and Pdg(i)

The green curve represents the power contribution by supercapacitor, after T = 2000s where it becomes the dominant power provider. Its rapid fluctuations and high-power levels reflect its role in handling transient and peak loads. The battery, supercapacitor, and diesel generator work together in a well-coordinated manner, demonstrating the HESS's capability to efficiently manage varying load conditions. The diesel generator delivers a steady base load, the battery supports periods of lower demand, and the supercapacitor responds to high power requirements and rapid fluctuations.

IV. CONCLUSION

This research demonstrates how to optimize a Hybrid Energy Storage System (HESS) for an electric ship through the application of a Genetic Algorithm (GA) in the MATLAB simulation environment. The main goal is to reduce overall expenses covering the installation cost, maintenance cost, and replacement cost while ensuring that both of the battery and the supercapacitor effectively manage normal load demands and fluctuating power demands. The results obtained verified that the battery's optimized rating of 100 kW and the supercapacitor's optimized rating of 301.19 kW are appropriate for their respective function. The optimal energy capacity of battery is 121.27 kWh which the battery could support the normal load operation, while the energy capacity of supercapacitor is 109.86 kWh which means that the supercapacitor effectively managed high power and fast transient loads. This approach to power distribution reflects established best practices in HESS design and underscores the value of coordinated component operation under varying load conditions. Over a 20-year period, the total project cost is estimated at $ 1,390,422. The Genetic Algorithm-based optimization proved to be a dependable strategy for ensuring the HESS meets technical requirements, maintains economic viability, and delivers stable performance.

Future studies could enhance system resilience and efficiency during unforeseen marine operations by integrating adaptive control methods and real-time load prediction.

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