Optimization of Hybrid Battery-Supercapacitor Storage System in Electric Ship Using Multi-Objective Genetic Algorithm

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***Abstract*— As the marine industry now is running toward the green and more efficient propulsion system, the optimization has also become a primary part of the research. This research study is focusing on the optimal sizing of Hybrid Energy Storage (HESS) in electric ship using Multi-Objective Genetic Algorithm (MOGA). The objective is to minimize the total cost of HESS and reducing battery degradation while maintaining the energy deliver during ship operation. By integrating a proposed Energy management system (EMS) alongside with the proposed HESS, helps coordinate the power allocation between battery and SC handling load demand. The results demonstrate that the optimized HESS effectively reduced operational cost, smoothen load fluctuation while mitigate battery stress under dynamic conditions.**

Keywords—Hybrid Energy Storage System (HESS), Battery, Supercapacitor, Multi-Objective Optimization, Electric Ship

NOMENCLATURE

Abbreviation

LIB	Lithium-ion battery
SC	Supercapacitor
HESS	Hybrid energy storage system
ESS	Energy storage system
EMS	Energy management system
O&M	Operation and maintenance
SOC	State of charge
GA	Genetic algorithm
MOGA	Multi-objective genetic algorithm

Mathematical symbols

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
$P_{d,i}$	Power demand over time (kW)
$P_{Bat,i}$	Power allocation of battery over time (kW)
$P_{SC,i}$	Power allocation of SC (kW)
P_{th}	Power threshold (kW)
$E_{Bat,i}$	Energy of battery at each time step (kWh)
$E_{SC,i}$	Energy of SC at time step (kWh)
C_{HESS}	Capital cost of HESS ($)
$C_{o\&m}$	Operational and maintenance cost of HESS ($)
ab_1	Power cost of battery ($/kW)
ab_2	Power cost of SC ($/kW)
ac_1	Energy cost of battery ($/kWh)
ac_2	Energy cost of SC ($/kWh)
$C_{B,o\&m}$	O&M cost of battery ($)
$C_{SC,o\&m}$	O&M cost of SC ($)
B	O&M cost coefficient of battery ($/kWh/year)
C	O&M cost coefficient of SC ($/kWh/year)
L_p	Lifetime project (year)
d	Discount rate (%)
Δt	Time step (second)
E'_{Bat}	Actual energy of battery (kWh)
A	LIB charge/discharge actual times (cycles)
η_{Bat}	Efficiency of battery (%)
$\eta_{Bat,dis}$	Discharge efficiency of battery (%)
$\eta_{Bat,inv}$	Battery converter efficiency (%)
$\eta_{Sc,dis}$	Discharge efficiency of SC (%)
$\eta_{Sc,inv}$	SC converter efficiency (%)
N	Total rated cycle life of battery (cycles)
ROC_B	Battery rate of change (kW/h)
SOC_{Bat}	SOC of battery (%)
SOC_{SC}	SOC of SC (%)

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I. INTRODUCTION

In this technology era, the marine application has been updated with numerous advance technologies by the intention of running toward a green, clean and sustainable development goal. Electric ship, with HESS offered numerous benefits, helping with the environmental issue by reducing the amount of the emission released by running the electric ship. As for others benefits, they offer a higher energy efficiency, reducing carbon emission and also give a more reliable operational flexibility to the system [1],[2].

HESS is known as a combination of two or more types of energy storages such as batteries, SC, flywheel, fuel-cell, etc. The integration helps strengthen the operation and also improve the efficiency of the ESS by helping the operation run more smoothly. On the other hand, HESS also offers additional benefits in term of giving a good lifespan, performance, operational efficiency and also giving a more cost effective to the ship owner [3], [4].

Optimization of the operation of HESS in electric ship encounter numerous challenges as it required critical ideas or variable to take into account such as considering the balancing between the energy efficiency, power delivery, cost, system longevity, etc [5]. And the optimization also holds a complex challenge as it emerges to a more mathematical approach to solve the problem. The higher expectation for the system we have the more complex of the objective function and the constraints of it gets [6].

In this present time, there are a wide range of studies conducted on the optimal sizing of HESS with a good control and management strategy. The optimal sizing that use the optimization method emphasized the economic benefits and operational efficiency gains [7]. For instance, the Non-dominated Sorting Genetic Algorithm (NSGA-II) in [8] has been used to design HESS for electric ship with cost-effective vision in which capable of managing power fluctuation and power management.

Similarly, HESS and Particle Swarm Optimization (PSO) was used in [9], to mitigate the voltage fluctuation by stabilize the bus voltage, which then enhance the sailing safety during high-load demand. A challenge of torque fluctuation and power instability for electric ship propulsion have been addressed in [10], to enhance the system performance by using a novel hybrid EMS.

Recent study also applied the deep reinforcement learning (DRL)-based EMS for a hybrid electric ship where this study was performed to explore the intelligent control scheme. As the result it is outperforming the traditional methods such as dynamic programming and sequential quadratic programing [11].

Beyond the marine application, HESS system was also been proposed in [12], for the microgrid with the goal of enhancing the stability and the efficiency in micro-grid. In automotive sector, introducing a new EMS in [13], for fuel cell/battery hybrid vehicle to overcome a lifespan challenges and reducing the cost of the application. A new model and control strategy was proposed in [14], for optimizing the performance of fuel cell electric hybrid vehicle has demonstrate that the capacitor can enhance fuel efficiency and stabilize the SOC.

To address optimal scheduling concern in [15], caused by the integration of solar power and energy storage, GA with varies optimal constraints was introduced. Applying some cases scenario with improvement on the optimization method demonstrate that it helps lower the cost and make less environmental impact. A Hybrid Electro-Thermal Model (H-EDM) utilize MOGA was introduced in [16], to manage the issue of fast charging in LIB result in enhancing the state of health (SOH) by creating the optimal charging profile within battery limit or constraint.

Moreover, the study approach in [17], was used to evaluate the benefit of integrating wide bandgap (WBG) technology-based bidirectional interleaved HV DC/DC converters into battery electric vehicles (BEVs). By applying MOGA to optimize the component selection for better drivetrain efficiency, the result shows off with a better performance including the reduction of energy consumption, faster acceleration with the efficiency increasement compare to the conventional electric drivetrain.

In the green shipping context where the DRL-based EMS was proposed in [18] to handle PV uncertainty while optimizing power contribution between HESS energy devices, showing by the improvement on operational efficiency under renewable fluctuation condition.

This research study aims to do the optimization using MOGA to make an optimal solution that lower the cost of HESS and minimize the degradation of the battery with various constraints including power balance, energy balance, ROC, etc. The purpose of this paper will also provide a good EMS strategy for the proposed HESS in order to smoothen the load fluctuation which cause by the load demand during the operation. MATLAB script will be using to implement and generate the result for the optimization while the propulsion load data will be a historical data provided by a Seabus.

The structure of this paper is organized as follows: Section II will detail make a detail methodology including element under study, decision variable, objective function, constraints, overview of MOGA and MOGA implementation. Section III will show the results and discussion. Finally, the conclusion will be presented in Section IV.

II. Methods

A. Element under Study

1) Seabus Data collection

The case study Seabus, is a 11 meters cargo vessel that use the electrification of the offshore patrol to charge the proposed HESS system and use only the HESS to supply the ship during the operating time. The dimension of the cargo ship will be provided by the following information and its drawing model will be shown in **Figure 1** [19] and more information about the ship can be found in [19].

The system used in this research is electric ship that required maximum power demand of 352 kW and the minimum is 0 kW, without charging process which mean in our case study we only make HESS discharge during the operational state. There will be 3 trip per day, the annual operation will be about 200 days, which make the annual total trip be 600 trips.

2) HESS

The proposed HESS architecture consists of two main energy elements such as LIB and SC. Each storage element connects with the system through an individual DC-DC converter that help manage the current and voltage of the storage device. At the output side, both converters are connected to the DC bus which help allow the power flow to a DC-AC inverter. As we notice that, the inverter will combine the DC power into AC power to meet the load requirement. The proposed HESS topology where LIB can be seen as HE cells and SC can be seen as HP cells as shown in **Figure 2** [19].

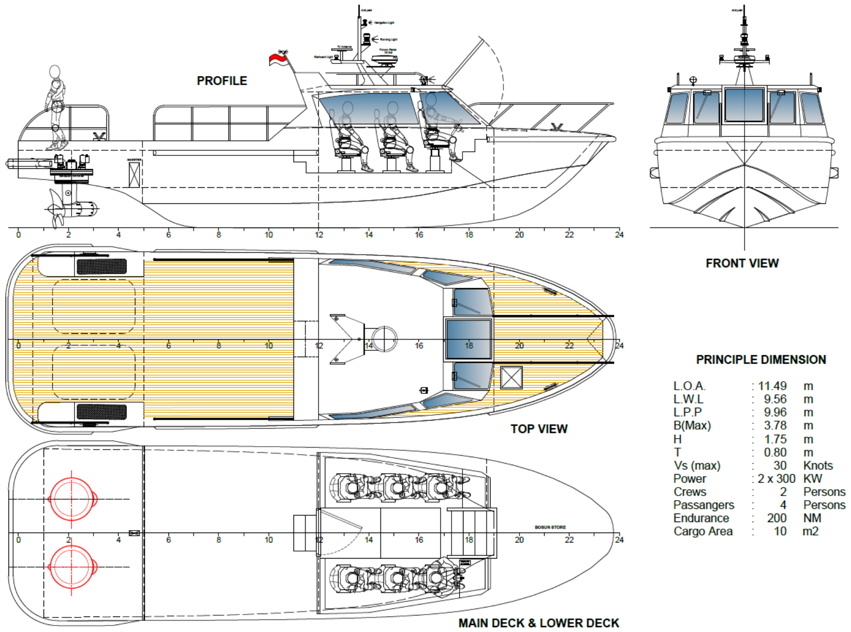

Figure. 1. The Drawing Model of Seabus

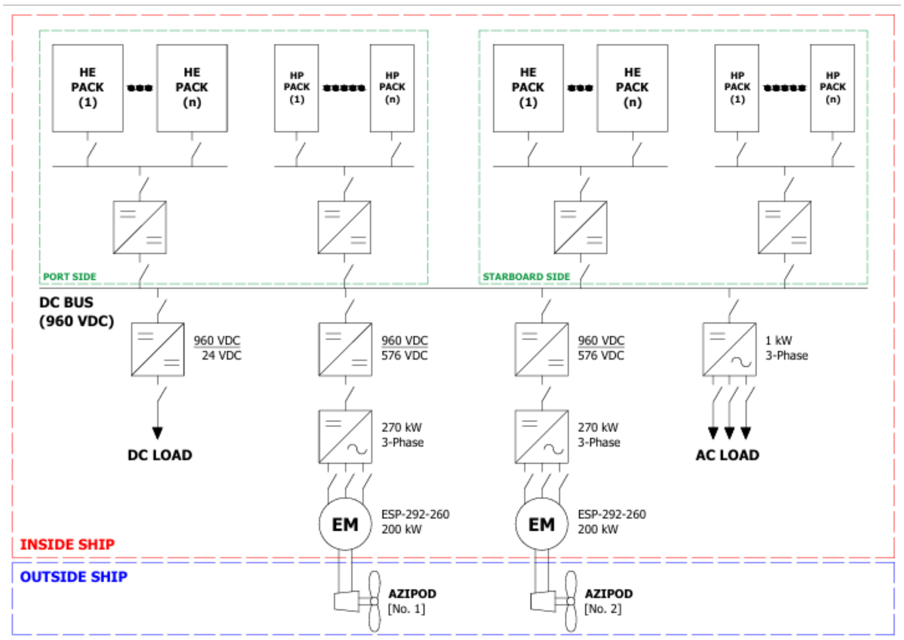

Figure. 2. The Proposed HESS Topology.

3) Battery

LIB is an energy storage device that store chemical energy through the electrochemical reaction. LIB can store a good amount of energy as it has high energy density, which make it suitable for the application that required long term energy storage. LIB also have lower self- discharge and could be considered as a clean energy as it could be used to replace the typical devices that use fossil-fuel. To achieve a required capacity of battery storage, the single cell of LIB needs to be connected in series or parallel. The battery considered in this research study is LIB which has the capacity of 1kWh and the upper limit of ROC is set to 21 kW/h [8].

4) Supercapacitor

SC is the energy storage that could be as the opposite of the LIB as it has high power density and lower energy density. One of its benefit in HESS storage is that it is being use to cover high frequency load. As for the SC, in our case study we will use Maxwell technology in [20] that has capacity of 600F with the rated voltage of 2.7V.

B. Decision Variable

Decision variable in this study research are the rated elements of HESS such as rated power and energy of both battery and SC. In addition to these design variables, the control variable such as the power allocation over time for battery and SC. The decision vector X can be expressed by:

$$X = (P_{Bat}, P_{SC}, E_{Bat}, E_{SC}, P_{Bat,i}, P_{SC,i}) \quad (1)$$

C. Objective Function

This research study aims to minimize the total cost of HESS and reduce battery degradation. These two ideas often conflict with each other. Reducing the cost of HESS will result in aggressive use of battery, which then will accelerate the degradation that leads to the increasement of cost. For instance, deep discharging might make a reduction on the expenses of HESS but will shorten the battery life.

Oppositely, to preserved battery health by limited the SOC, can minimize the degradation but will leads to underused of battery result in high cost of HESS.

Therefore, multi-objective optimization approach is necessary in this case, as it can capture this trade-off. The multi-objective formulation in this work will enable a set of non-dominated solution that represent different trade-off between the two objectives by ensuring the cost efficiency and system longevity.

By this approach, the decision maker can select an appropriate solution from a Pareto set based on operational priority and constraint or long-term performance goals.

1) Cost of HESS

The total cost of the system is really important as it is the cost where we need to determine or estimate in order to know how much the HESS system will cost or whether it is suitable for the budget of our project or not.

The HESS is consisted of two main elements such as the battery and the supercapacitor. And for proposed system total cost consists of the capital cost of each consisted element in HESS and the operation cost and maintenance cost. The mathematical equation of the total cost can be obtained by [21]:

$$f_1 = C_{HESS} + C_{o\&m} \quad (2)$$

The total cost of the energy storage device is obtained by [8]:

$$C_{HESS} = ab_1 P_{Bat} + ab_2 E_{Bat} + ac_1 P_{SC} + ac_2 E_{SC} \quad (3)$$

The operation and maintenance cost of the energy storage device in this paper is determine by the sum of the cost of operational and maintenance cost of battery and supercapacitor, by utilizing the Net Present Value (NPV) with Uniform Series Worth (USW) factor to convert annual expenses into present value. The operational and maintenance cost of the energy storage can be obtained by [21] :

$$C_{o\&m} = C_{B,o\&m} + C_{SC,o\&m} \quad (4)$$

$$C_{B,o\&m} = B \times E_{Bat} \frac{(1+d)^{L_p} - 1}{L_p (1+d)^{L_p}} \quad (5)$$

$$C_{SC,o\&m} = C \times E_{SC} \frac{(1+d)^{L_p} - 1}{L_p (1+d)^{L_p}} \quad (6)$$

2) Battery Degradation

The degradation of battery and supercapacitor is one of the criteria that we need to consider and take into account as it could affect the system efficiency and its well-being. LIB usually have a cycle life of 3000 to 6000 cycles and often involve in the complex reaction during the charge and discharge time in which effect the battery life that can lead to deterioration of LIB. As for SC, the service life of SC is up to 10 years or more, so, in this study research, the life loss of SC is neglected. The relationship between the total output power and the maximum energy of the battery during the operation in discretization formula can be defined by the ratio which can be obtained by [22]:

$$A = \frac{\sum_{i=1}^{n} (P_{Bat,i} \Delta t)}{E'_{Bat}} \quad (7)$$

The energy flow through the battery during n total number of sampling points where we only put the battery through the discharge state during the operational process can be obtained by:

$$E'_{Bat} = E_{Bat} \eta_{Bat} \quad (8)$$

The lifetime loss of battery can be defined as a ratio between the equivalent full charge/discharge cycle during project lifetime and total rated cycle life of battery which can be express by:

$$f_2 = \frac{A}{N} \quad (9)$$

D. *Constraints*

1) Power Balance Constraint

The power balance constraint ensures that the total power that the source provided will meet the power demand of the ship at all times. This is crucial to maintain the operational integrity of the ship. If the power supplied does not meet the demand, it can lead to system failures and the operational disruptions [8].

$$P_{d,i} = P_{Bat,i} + P_{SC,i} \quad (10)$$

2) Power Limit and SOC Constraint

It is crucial to limit the charge and discharge power and of HESS component as the excessive of charging and discharging of energy devices can accelerate the degradation, failure rate and reduce safety. Therefore, HESS storage will need to meet some requirements below:

$$-P_{Bat} \leq P_{Bat,i} \leq P_{Bat} \quad (11)$$

$$-P_{Bat} \leq P_{Bat,i} \leq P_{Bat} \quad (12)$$

$$SOC_{Bat,min} \leq SOC_{Bat,i} \leq SOC_{Bat,max} \quad (13)$$

$$SOC_{SC,min} \leq SOC_{SC,i} \leq SOC_{SC,max} \quad (14)$$

3) Energy Constraint

The energy constraint ensures that the total energy which provided by both battery and SC will meet the demand of the ship at all times. So, the energy store in the battery and SC must be greater than the maximum energy demand by the load.

$$E_{Bat} \geq \frac{\left| \frac{\max(E_{Bat,i})}{\eta_{Bat,dis}\eta_{Bat,inv}} \right|}{SOC_{Bat,max} - SOC_{Bat,min}} \quad (15)$$

$$E_{SC} \geq \frac{\left| \frac{\max(E_{SC,i})}{\eta_{SC,dis}\eta_{SC,inv}} \right|}{SOC_{SC,max} - SOC_{SC,min}} \quad (16)$$

$$ROC_B = \frac{|P_{Bat,i} - P_{Bat,i-1}|}{\Delta t} \quad (17)$$

The pararmeters used in this proposed HESS will be shown in **Table 1** [8], [21], which describe the lifetime period of the project while mentions about the necessary elements use in the HESS. The cost of power and energy will provide by [8] and will be converted from Yuan to USD by exchange rate of 1 Yuan equal to 0.1388 USD.

TABLE 1.
PARAMETERS USED IN PROPOSED HESS [8], [21]

Parameter	Value	Unit
ab_1	374.78	\$/kW
ab_2	88.84	\$/kWh
ac_1	138.81	\$/kW
ac_2	3748.76	\$/kWh
B	19.77	\$/kWh/year
C	10	\$/kWh/year
L_p	10	year
d	5	%
$\eta_{Bat,dis}$	90	%
$\eta_{Bat,inv}$	100	%
$SOC_{Bat,min}$	20	%
$SOC_{Bat,max}$	80	%
$\eta_{SC,dis}$	95	%
$\eta_{SC,inv}$	100	%
$SOC_{SC,min}$	10	%
$SOC_{SC,max}$	90	%
N	2640	cycles

E. Overview of MOGA

GA represents a type self-adaptive global search optimization technique inspired by natural selection. The candidate solution is developed by the crossover, mutation and selection in population-based search. This make GA effectives for resolving the multi-modal, non-convex, non-linear problem, including those with continuous and discrete decision variables [23].

MOGA is a better extension of GA design specifically to handle multiple, often conflicting, objectives. It uses a guided random search approach capable of exploring various regions of the solution space. As a result, MOGA can find a wide range of solutions with multiple variables optimized at once. The optimal results form a Pareto set, which consists of non-dominated solutions—those where achieving one objective would worsen another. The corresponding values in the objective space are known as the Pareto front [24].

In this research study, MOGA is used to optimize the HESS system by minimizing cost and battery degradation. Starting with a set of potential HESS configurations, the algorithm iteratively develops them through genetic operations. To guarantee that the solutions generated are practical and physically feasible, constraints such as SOC limits and power balance are applied at every generation. A Pareto front of optimal trade-offs is constructed using the non-dominated sorting method. This provide a set of configurations giving a different balance between cost and degradation, enabling adaptive choice. Another good point of using MOGA is that it generates divers and unbiased optimal solution aligning well with the objective of this study.

F. MOGA Implementation

The flowchart of the proposed system using MOGA is shown in **Figure 3**. The step of Cost effective and degradation using MOGA will be following by [25]:

Step 1: Start the optimization process by using the MOGA as our optimization method

Step 2: Generate the initial population of solution randomly and each particle will represent a collection of variables

Step 3: Evaluate fitness. Each individual will be evaluated by two objective function which are cost of HESS and degradation of battery and then modified with the defined constraints

Step 4: In this Non-Dominated sorting stage, the solution will be ranked based on the pareto dominee and the best trade-off solution included in the first pareto front where the no solution is clearly not better than others following by the next that slightly less optimal but still considered as a good useful and divers

Step 5: In this selection process, the individual will be selected for reproduction based on their rank and crowding distance

Step 6: In this crossover and mutation stage, the operation will create new candidate solutions. This genetic operator will allow the algorithm to find new areas for solution space

Step 7: Convergence check. Making a decision whether the optimization should stop or continue. If it satisfied the setting constraints then the optimal solution is found. once the converge is found then extract the Pareto Front and then analyze trade-off between cost and degradation to select the best HESS configurations for the electric ship. But if the optimal solution does not satisfy then, the process will loop back to fitness evaluation stage again

Step 8: After the convergence process is reach then, the final Pareto front will be extracted. All of the solution will be represented the best trade-off based on the system priorities

Step 9: Then we can conclude the optimization process after getting a set of optimal solutions that satisfy our design protocols

III. Result and Discussion

The result in this paper was generated using MATLAB to do the simulation for the proposed HESS system. The goal of this paper was to minimize the cost of HESS and degradation of LIB using MOGA as the optimization method align with the useful constraints to generate the optimal solution for 10 years operational period.

The Pareto Front will be generated based on the trade-off between the cost and degradation with the existing load data. The following discussion section will be involved the graph analysis and result interpretation.

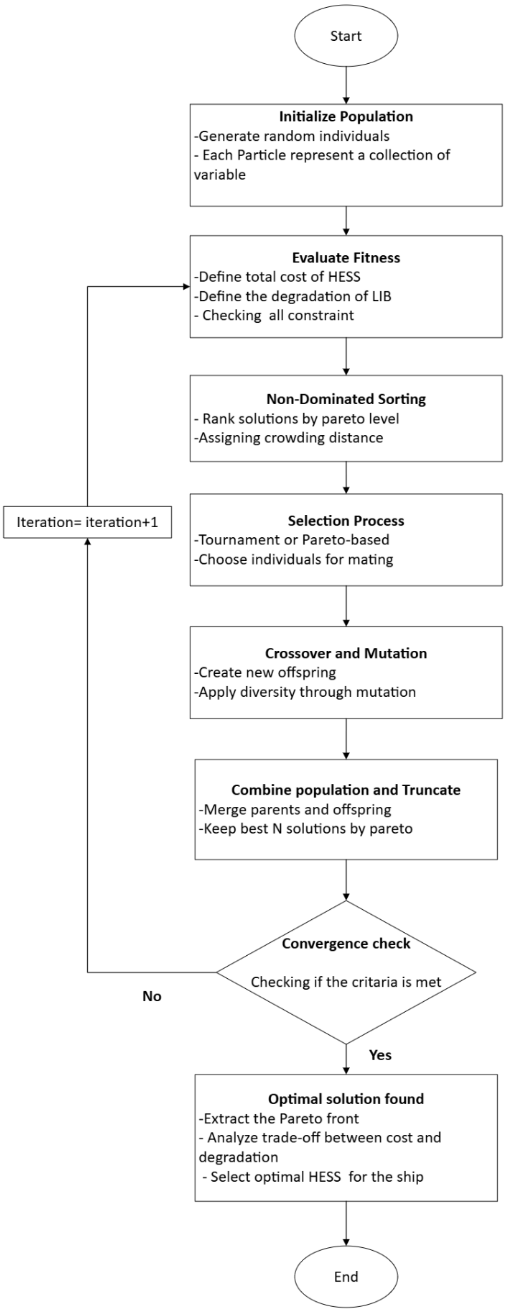

Figure. 3. Flowchart of MOGA

A) Power Consumption

The load demand consists of 5000 times step series power requirement in kilowatt (kW) over time interval. **Figure 4** [19] shows the existing load consumption of a Seabus consisting of a low and high-power demand period. The load starts with a slow yet increase steadily during the first 2000 seconds then following by a high phase which show by a rapid and aggressive load fluctuation condition. After the 3400 seconds, the load demand decreased gradually. Overall, the power consumption load profile is considered complex yet suitable for the research study as it gives a realistic challenge for the propose HESS system yet it also has both steady-state and transient components.

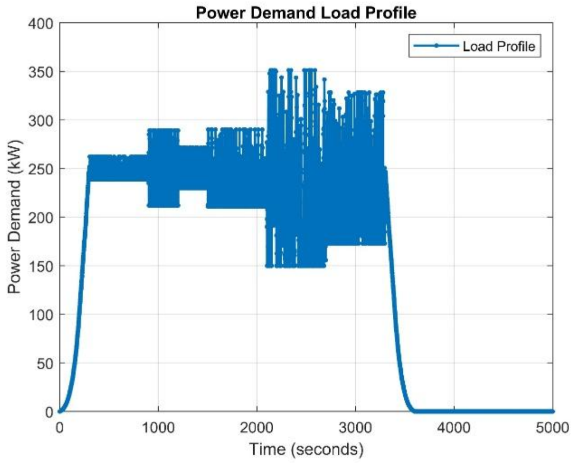

Figure.4. Load Consumption

B) Energy Management System (EMS)

Due to the power variation bring by the dynamic load, it is really necessary to maintain a proper power management to ensure the system stability against the load fluctuation.

The propose EMS strategy has the intention of ranging the power split between battery and SC to maintain the stability of the system and ensuring the availability of the storage for future usage. To maintain this goal, EMS will divide the total power demand into two operating condition:

- High power demand: There will be only 35% of the load in which will consider as the high load demand

Normal or low power demand: In this operating state, both LIB and SC will contribute to cover the load demand

The EMS strategy will follow by the following steps and its flowchart will be shown in **Figure 5**.

Step 1: The EMS will start the operation by initialize all the necessary parameter then prepare for reading the load demand

Step 2: At each time step the system will start by reading the power demand at i-th time, so that, it will know how much power supplied needed for the load

Step 3: In this step, the pre-defined power threshold (P_{th}) will be calculated to classify the type of load

$$|P_{d,i}| > P_{th} \tag{18}$$

Step 4: At this point, the EMS will define the type of load demand whether it is in high, normal or low load demand.

- High demand: SC will contribute more.

$$|P_{Bat,i}| \leq |P_{Sc,i}| \tag{19}$$

- Normal or Low Demand: Battery will contribute more.

$$|P_{Bat,i}| \geq |P_{SC,i}| \tag{20}$$

Step 5: The energy share constraint will be applied to ensure the fair usage as the battery will share a 45% minimum portion of energy over a cycle.

$$\sum(P_{Bat,i}) \geq 45\%(P_{Bat}) \tag{21}$$

Step 6: Before dispatching the power, the EMS will check the SOC of both energy storage devices

- If one of the devices is below theirs minimum SOC then EMS will adjust their power base on the available energy storage
- If SOC of both devices is sufficient to supply for the load then, it will be applied the power split plan

Step 7: Power will dispatch from both devices according to step 4,5 and step 6

Step 8: EMS will update the SOC of energy devices based on power delivered

Step 9: The time step will be continued and EMS will loop to step 2 by continue reading the next load until the end of time horizontal

Step 10: EMS will stop at the end of the time

A)Power Allocation

The comparison of total power consumption and the power supplied by HESS during the operation period is shown in **Figure 6**. The curve show that the power supplied is successfully satisfy the load demand profile throughout the simulation period, which can be determined that the proposed energy devices component is capable of supplying both steady and fluctuating power requirement. This also confirm that proposed HESS system is able to track down the load variation effectively by coordinating the HESS components output respectively.

The individual or a detail power output of battery and SC is shown in **Figure 7**. As shown, the battery begins to support the load demand early with a steady supply to avoid the rapid load fluctuation that could increase the battery degradation. On the other hand, the SC is mostly inactive during the early stage, then start to contribute significantly when the load became highly dynamic during 2000 seconds to 3400 seconds. During that time, SC seemed to respond to a rapid load fluctuation with a sharp rise and drops in power. The behavior of both energy components show that the power sharing strategy had effectively assigned suitable role based on each devices strength which reduce stress on battery while enhancing the system efficiency.

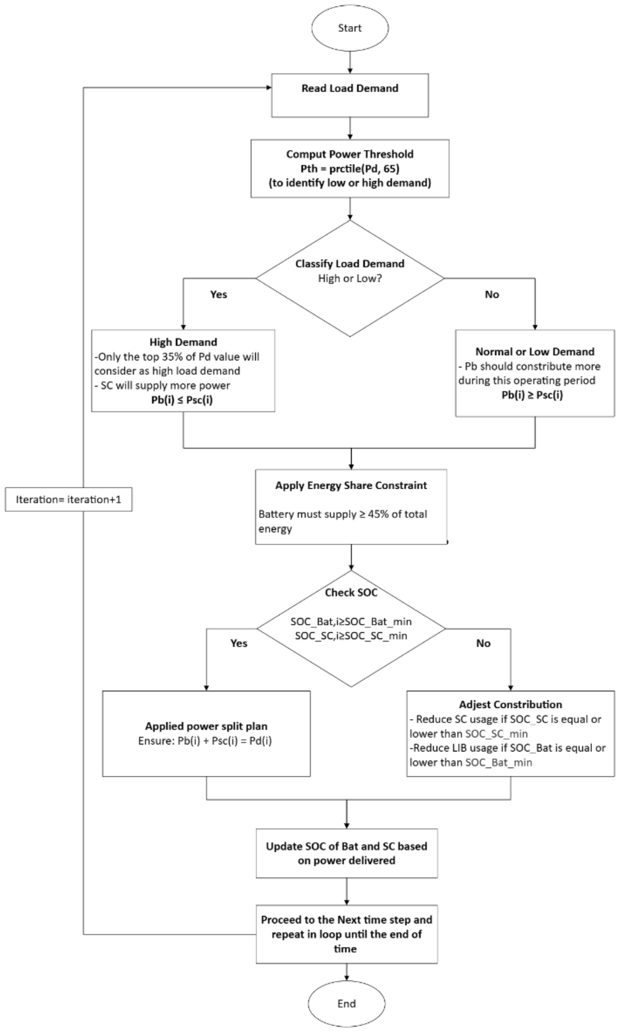

Figure. 5. The Proposed EMS Flowchart

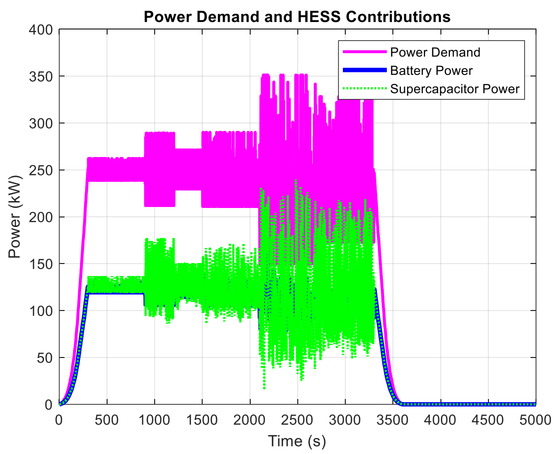

Figure.6. Power Demand and HESS Contribution

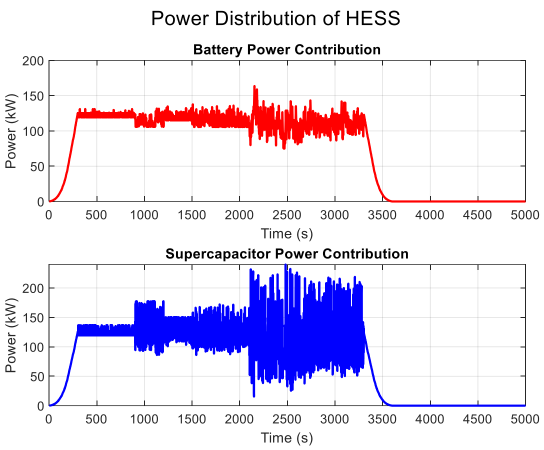

Figure.7. Power Distribution of HESS

B) Pareto Front

The Pareto front of the proposed HESS is shown in **Figure 8**. Each point in the graph represent the non-dominated solution which balancing out the trade-off between the Cost of HESS and Degradation of the battery.

There are three highlighted key points annotated in the graph such as the Low, Balanced and High Cost.

- **Low Cost:** This point has achieved a good economic value but it gave off the highest battery degradation which indicate that while the expense reduced, the battery will undergo a short lifespan.
- **Balanced:** This point offers a compromise solution between the economic and the battery lifespan, which can be guarantee and consider a long-term operational system
- **High Cost:** This point solution might seem to reduce the battery degradation but it gave a high total cost due to the oversizing the system

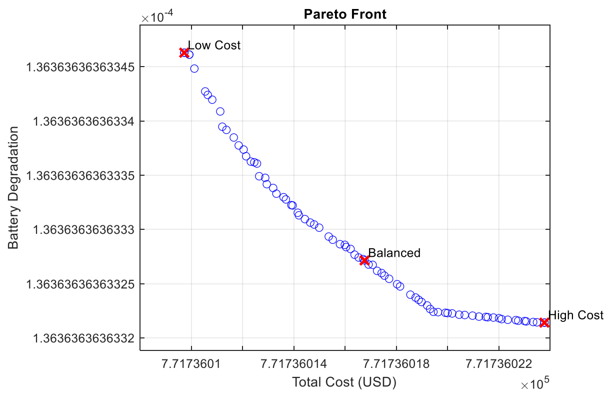

Figure. 8. Pareto Front

The Pareto front of the highlight points show the reverse or the conflict behavior of both objective functions, when reduce one will potentially increase the other.

A) Final Design of HESS

Based on the analysis of Pareto front, the Balance option is selected for the final evaluation, as it gave off a suitable trade-off between cost and degradation. The rated value of the Balance option will show in **Table 2**.

TABLE 2
RATED RESULT OF FINAL EVALUATION DESIGN

Component	Rated Power (kW)	Rated Energy (kWh)
Battery	163.63	316.29
Supercapacitor	239.74	173.10

The rated value in **Table 2** has indicated that the high value in power of SC ensure that it absorbs the fluctuated load well while LIB on the other hand, maintain a smoother power range to avoid discharging cycle that deteriorate the battery.

The corresponding battery degradation value is 0.00013636, a ratio represents of battery cycle life use in this project which is equal to 0.013636% of battery's total cycle life. Showing the minimal life loss of battery during the lifetime project. Due to SC contribution in handling the transient power demand in which make it more effective in reducing battery stress resulting extending its usable lifetime.

Noticeably, the total cost of the chosen solution is approximately $ 771,736 which is remain identical to the low-cost solution, showing that improving the battery degradation does not necessary giving additional price to the economic value.

In summary, the optimal result shows a clear evident of how well the HESS storage configuration meets the demand while balancing out the cost and degradation. The analysis also illustrated on how the energy sharing strategy work by responding to the load demand over time as SC managing the high fluctuating power, while battery contribute to the energy delivering. Moreover, the pareto front also show a trade-off between the cost efficiency and improving battery lifespan. By analyzing load profile, load response characteristics, and sizing outcomes, the study confirms that multi-objective optimization provides a clear and effective solution to achieving technical performance, economic viability while improving battery life.

IV. CONCLUSIONS

This study had presented a multi-objective optimization framework for a HESS by integrating LIB with SC to manage fluctuating power demand while minimizing overall system cost and battery degradation. A Range of the optimal solutions was generated using MOGA, reflecting trade-offs driven by an amount of constraints and multi-objective decision making. The result demonstrate that SC is effectively mitigate the peak load impact while reducing battery stress resulting in lower degradation. The balanced design achieves comparable cost performance to high-cost alternatives, indicating that SC integration will not compromise economic efficiency.

Importantly, by adding degradation into the optimization remains valuable, as it gives a better power allocation behavior and help the system prepares for future applications where battery degradation and stress are more critical. By analyze the power allocation, load dynamics, and Pareto front behavior, help provides more evidence that degradation-aware optimization supports informed decision-making in energy storage planning. These helped highlight the importance of scenario selection, energy sizing, and load characteristics when evaluating HESS performance.

Regarding the future work, we plan to build up upon the current study by including the real time energy strategy along by adding the renewable energy source, which will give a more practical HESS model. Additionally, more adaptive control algorithm, more detail battery degradation model and a bunch of broader case study will be added to expand the design space where HESS provides a better and greater solution

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