메타휴리스틱 접근 기반 직류 선박 마이크로그리드의 최적 에너지 관리 시스템

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Optimal Energy Management System Based on Metaheuristic Approach for DC Shipboard Microgrids

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ABSTRACT

This paper introduces a novel energy management algorithm that integrates a DC microgrid with an existing shipboard power network powered by diesel generators. The algorithm comprises two stages focused on optimizing the dispatchable components within the system. The implementation and testing of the optimization algorithm have been conducted using the MATLAB platform. The proposed algorithm offers promising results and demonstrates the potential for efficient energy management in shipboard power networks. The combination of the DC microgrid and the algorithm holds significant potential for enhancing the overall performance and sustainability of shipboard power systems.

1. Introduction

The traditional shipboard system typically relies on diesel generators, which can generate pollution due to their inefficient operation and create an uneconomical system [1].

Since the voyage mode of a ship is an islanded mode, it is crucial to regulate the voltage of the shipboard microgrid (SMG). However, due to variations in speed and weather conditions, the SMG operates under various load profiles while at sea. Consequently, generators may operate under hazardous conditions, such as overloading and low loading [2]. In particular, running diesel generators at low loads can cause low pressure, smoke particles, and increased pollution, all of which can shorten their lifespan. Additionally, the loading on the diesel generators affects emissions and specific fuel oil consumption (SFOC).

The integration of SMGs with a battery pack, as described in [3], addresses this issue by allowing engines to operate at optimized points for better fuel efficiency and lower emissions. However, there are limitations to using batteries since they are designed to operate at a specific discharge rate and cannot exceed that value [4]. Additionally, since there is no provision for charging the batteries during sailing operations, they become useless during overload conditions if they are drained. Although increasing the power rating of the batteries may solve this problem, it will also increase the size and weight of the shipboard.

This study proposes a hybrid storage system that combines fuel cells and batteries to support diesel generators more efficiently. To achieve this, the study proposes an effective metaheuristic approach based on an Energy Management System (EMS) algorithm.

2. System Architecture

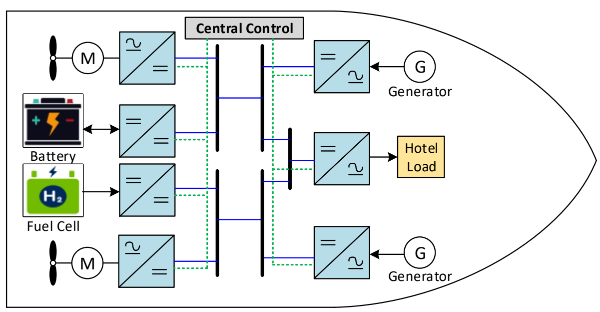

Fig. 1. Shipboard power system architecture.

A simple and redundant DC shipboard microgrid structure is considered for this study, as depicted in Figure 1. In addition to diesel generators, the existing system is integrated with one battery storage system and one fuel cell system.

2.1 Diesel Generators (DG):

To estimate the fuel consumption costs for fuel cell (FC) generators, a non-linear relationship between FC power and fuel consumption is employed [5]. Consequently, the FC cost equation can be expressed as follows:

$$C_{\_DG} = \Delta T(a_1 P_{\_DG}^2 + b_1 P_{\_DG} + c_1) \qquad (1)$$

where a_1, b_1, and c_1 represent the constant coefficients, and their respective values are provided in Table 1. $P_{\_DG}$ denotes the power supplied by the generator.

2.2 Fuel Cell:

A non-linear relationship between FC power and fuel consumption is used to estimate fuel consumption costs for FC generators [6]. As a result, the FC cost equation can be represented as,

$$C_{\_FC} = \Delta T(a_2 P_{\_FC}^2 + b_2 P_{\_FC} + c_2) \qquad (2)$$

where, a_2, b_2, and c_2 are the constant coefficients, and $P_{\_FC}$ is the power output of the fuel cell.

Table 1. System parameters

Component	Rated values
Diesel generator	P = 2 x 88 kW, 440V, 50Hz
	a_1 = 0.0013 $/kW, b_1 = 0.27 $/kW, c_1 = 2.13 $
Propulsion motor load	P = 2 x 100 KW
Fuel cell	P = 50 kW, 650 V
	a_2 = 0.000315 $/kW, b_2 = 0.047 $/kW, c_2 = 0.13 $
Battery	160 Ah, 650 V
DC bus voltage	750 V
Hoteling load	P = 30 KW

2.3 Battery Storage System (BSS):

The Battery Storage System (BSS) is highly favored due to its widespread availability and advanced technology. In this study, lithium-ion batteries are chosen as they offer higher efficiency and power density compared to other alternatives. The cost of battery power can be determined using the following equation:

$$C_{\_b} = \left(\frac{C_{tot}}{L\eta^2 E_{b,r}} P_{\_b} \right) \Delta T \tag{3}$$

$$L = 694\left(DoD^{-0.795}\right) \tag{4}$$

$$DoD = 1 - SoC \tag{5}$$

where C_{tot} and $E_{b,r}$ represents installation cost of battery and rated capacity of the battery, respectively. L is a function of DoD, where DoD and SoC stand for the depth of discharge and state of charge of the BSS, respectively. The energy available in the battery is represented by

$$E_{\_b}(t_2) = E_{\_b}(t_1) - \Delta T\left[P_{\_b}(t_1)(\delta_{ch} - 1) + P_{\_b}(t_1)(\delta_{dis})\right]. \tag{6}$$

2.4 Loads:

This study considers two distinct types of loads. The first type is the propulsion motor load, which is responsible for driving the propellers. The second type is the hoteling load, which includes various electrical devices such as lights, washing machines, entertainment systems, and more.

3. Problem Formulation

3.1 Objective Function:

The aim of this study is to reduce the overall operating cost of the system by intelligently managing the BSS and FC system based on the load profile. The function for optimizing the total costs can be expressed as follows:

$$f = \min\left\{C_{\_DG} + C_{\_FC} + C_{\_b}\right\}. \tag{7}$$

3.2 Constraints

This research incorporates two fundamental constraints. The first constraint pertains to the overall power balance within the system and is defined as follows:

$$P_{\_DG} + P_{\_FC} + P_{\_b} = P_{\_L}. \tag{8}$$

The second constraint involves limitations on the power output of dispatchable units. Each dispatchable unit must operate within predetermined boundaries, which are outlined below:

$$(-\delta_{ch})P_{\_b(\min)} \le P_{\_b} \le (\delta_d)P_{\_b(\max)} \tag{9}$$

$$0 \le P_{\_FC} \le P_{\_FC(\max)} \tag{10}$$

$$0 \le P_{\_DG} \le P_{\_DG(\max)} \tag{11}$$

$$E_{\_b(\min)} \le E_{\_b} \le E_{\_b(\max)} \tag{12}$$

where $P_{\_b(min)}$, $P_{\_b(max)}$, and $P_{\_FC(max)}$ represent the highest rates of power at which each component can operate within a given time interval T. The maximum limit of the diesel generator power are denoted by $P_{\_FG(max)}$, whereas the extreme limits of the BSS stored energy are denoted by $E_{\_b(min)}$ and $E_{\_b(max)}$.

4. Proposed EMS Algorithm

The EMS algorithm proposed in this study is presented in two distinct stages, which are sequentially followed as depicted in Fig. 2 and Fig. 3.

4.1 Stage I:

A rule-based method is employed in stage I as shown in Fig. 2. Here, P_L and P_{DG_rated} stands for the load power and rated power of diesel generator, respectively. SoC represents state of charge of the battery. Additionally, δ is a binary variable, which signifies the working condition of the battery. ('δ_{dis}' denotes discharging and 'δ_{ch}' denotes charging). Similarly, 'δ_{FC}' represents the status of diesel generator. This stage I selection will proceed to the stage II algorithm for optimization.

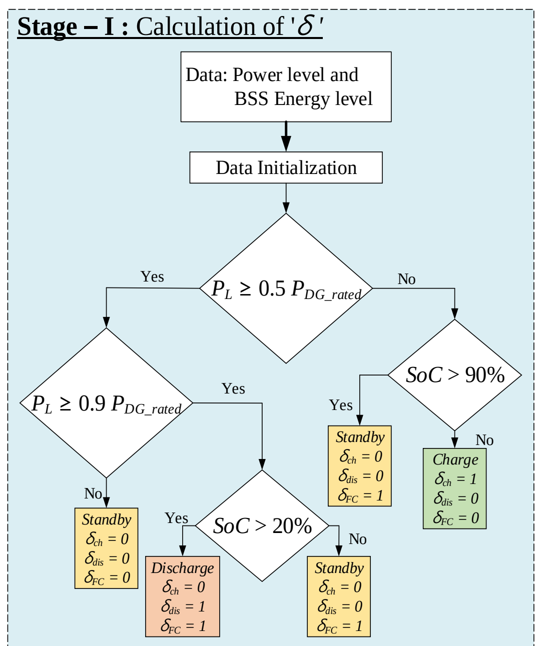

Fig. 2. Calculation of variable δ for respective components.

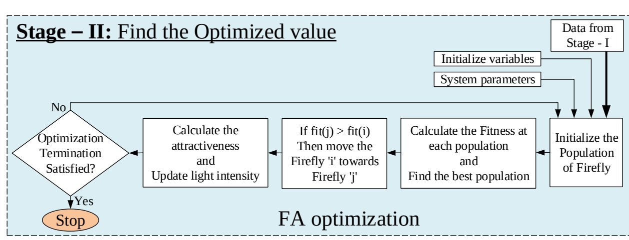

Fig. 3. Flowchart of firefly optimization algorithm.

4.2 Stage II:

The Firefly optimization algorithm is employed in stage II due to its numerous advantages over other widely used optimization techniques. These advantages include fast convergence and a reduced burden on the system. In the Firefly algorithm, two important factors are light intensity (brightness) and attraction. These factors play a crucial role in the optimization process.

The firefly that is more shining than the others will absorb the ones that are less bright and the brightness is decided by the objective functions. As fireflies move closer to each other, their attraction intensifies, and this attraction is influenced by their brightness. Conversely, when fireflies move apart, the attraction decreases. The Firefly algorithm aims to find the optimal scheduling parameters based on the stage I choice and initial values. It continues to search for the optimal value until it converges to an optimum solution.

5. Simulation Results

From the analysis of Fig. 4, it is evident that the output power generated by the diesel generator predominantly remains within the suggested optimum limit, ensuring its maximum lifespan. The operational range recommended by DG manufacturers (50% to 90% of the rated value) is well maintained for the diesel generator, as observed in the power profile. The system effectively handles overload situations by utilizing the power supplied by the fuel cell and battery, thereby preventing any strain on the diesel generator. Conversely, during underload conditions, the excess energy is stored in the battery, ensuring its efficient use to support the diesel generator when needed.

In the overall scenario, the diesel generator operates within its minimum and maximum optimum range, resulting in enhanced efficiency and longevity. The collaborative efforts of the stages I and II of the proposed EMS algorithm play a crucial role in achieving this optimal operation. The power profiles of the fuel cell and battery storage system, as depicted in Fig. 5, demonstrate the dynamic contribution of these energy sources in supporting the power demands of the system. Additionally, the energy profile of the battery (SoC) shown in Fig. 5 illustrates the effective operation of the battery by storing and suppling energy based on the system requirements, and further enhancing the overall performance and stability of the system.

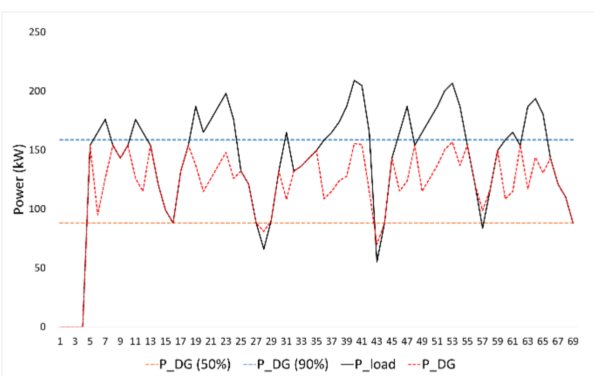

Fig. 4. Power profiles of diesel generator and total system load.

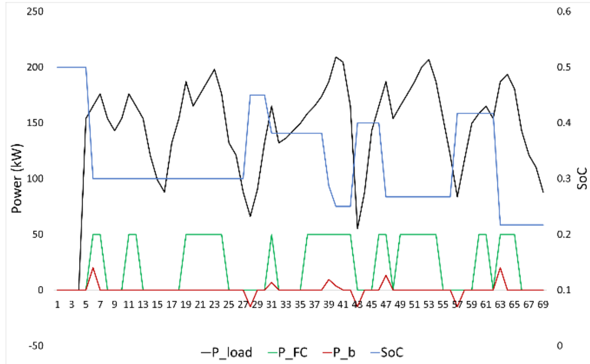

Fig. 5. Power profile of fuel cell, battery and total system load with SoC profile of the battery.

4. Conclusions

In conclusion, the proposed energy management system showcased in this paper has demonstrated effective operation of the diesel generator within its optimal range. By optimizing the energy resources of the system and leveraging the capabilities of the DC microgrid components, namely the fuel cell and battery storage system, the overall performance and efficiency have been significantly enhanced. This not only prolongs the lifespan of the diesel generators but also mitigates the environmental impact by reducing pollution. The findings of this study highlight the importance of implementing intelligent energy management strategies for achieving efficient and sustainable operation of shipboard power networks.

Acknowledgment

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