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Research paper

Optimizing dynamic electric ferry loads with intelligent power management

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ABSTRACT

In recent years, there has been an increasing shift towards using environmentally friendly renewable resources in marine vessels, replacing traditional diesel generators. However, one of the main challenges faced in renewable energy-driven marine vessels is dynamic load management. The feasibility of a renewable-powered electric marine vessel largely depends on the optimal utilization of renewable resources, and storage is an essential component of the marine electric vessel. This paper proposes a two-stage power management system (PMS) for an electric ferry powered by the fuel cell and battery energy storage systems (BESS). The primary objective of the proposed PMS is to ensure a balance between the generated power and the ferry load by minimizing the consumption of hydrogen (H_2) fuel. The first stage of the PMS employs particle swarm optimization (PSO), bacterial foraging optimization (BFO), and a hybrid PSO-BFO algorithm to optimize the fuel cell and battery capacity. This is done so that the generated power can follow the load demand. The second stage of the PMS utilizes the Mamdani rule-based fuzzy logic system (FLS) to match the load demand with the generated power. The hybrid PSO-BFO algorithm optimizes the fuzzy control parameters to meet the dynamic load by ensuring optimal H_2 fuel consumption and battery state of charge (SOC). To obtain optimal values, the load profile of a conventional ferry is used for the proposed PMS. Based on the optimization results, the optimal capacities are found to be 318 kWh and 317.64 kWh for the fuel cell and BESS, respectively, which are obtained using the hybrid PSO-BFO algorithm. The optimal value of H_2 fuel consumption during cruising is found to be 18 kg. A simulated model-based approach validates the operation of the proposed PMS. The proposed PMS ensures optimal H_2 fuel consumption and battery SOC while meeting the dynamic load demands of the ferry. The results obtained demonstrate the effectiveness of the proposed PMS in optimizing the renewable energy-driven marine vessel power system.

1. Introduction

The maritime industry is responsible for emitting approximately 1 billion tons of CO_2 and other greenhouse gases, accounting for approximately 3% of total greenhouse gas emissions (Greenhouse gas emissions from global shipping, 2022). To prevent marine air pollution caused by conventional diesel engine-based marine vessels, the International Maritime Organization (IMO) has ratified regulations (Smith et al., 2014). Around 90% of marine vessels still rely on diesel generators, despite their negative environmental impact, due to their high energy consumption, calorific value and efficiency in comparison to renewable energy sources. Though the alternate electrical power options for marine vessels are environmentally feasible, those options are still not financially viable because of the high cost of alternative electricity sources (Bayu et al., 2021). The high cost of alternate sources can be minimized by the optimal use of renewable resources for electricity generation which may draw the attention of ferry owners and operators to invest in hybrid and alternate source-based electric ferries (Bagalini et al., 2019). Hybrid marine vessels that combine renewable generation and storage can offset the high specific fuel oil consumption of diesel engines at low loads, resulting in fuel savings of 10–20% (Hansen et al., 2016). The variable speed diesel generators are commonly used in marine vessels to improve fuel efficiency.

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The nonlinear load characteristics of marine vessels are different than those of other nonlinear loads like EVs, battery powered mining and road trucks in terms of load pattern and extreme load variations. The electrical load of the marine vessel comprises of propulsion load and auxiliary load. The nonlinear propulsion motors are the main power consuming load which consumes significant electrical power during cruising (Smogeli, 2006). Seawater fluctuations can cause rapid changes in propulsion load, particularly during bad weather, leading to rugged mechanical wear and tear and increased fuel consumption and maintenance costs (Radan, 2008; Xie et al., 2023). The integration of rapid switching power electronics devices and multiple electricity sources including intermittent renewables in marine transport electricity systems has enhanced its nonlinearity. The unpredictable load power consumption can even cause blackouts in marine power systems. However, the inclusion of BESS (battery energy storage system) can assist in dynamic nonlinear load management, power quality, system stability and energy efficiency. To promote the adoption of renewable-powered electric vessels, research is necessary to determine the optimal use of renewable resources for managing dynamic nonlinear marine loads. Research on coordinating multiple power sources with energy-efficient operation is necessary for managing high dynamic marine loads, and an appropriate power management approach is essential for integrating renewable resources and BESS into marine power systems.

2. Literature review and problem statement

So far, several research works have been conducted on minimizing fuel saving by optimal power management of the electric ferry. Lorenzo Balestra et al. proposed simulation model-based energy management strategies for fuel cell and battery operated marine hybrid power systems (Mustafa et al., 2021). The proposed model mimics the actual response of the marine vessel's grid by analyzing different energy management strategies for optimizing H_2 consumption (Balestra and Schjølberg, 2021). This research lacks in identifying the load balancing technique for optimizing the H_2 consumption. The validation of the proposed approach does not support the research outcomes. To save fuel for the hybrid electric ferry, a meta-heuristic algorithm based power management system is proposed by Mondal et al. (2022). The proposed power management system used grey wolf optimization and fuzzy logic system to minimize the operational cost by considering operational and technical constraints (Al-Falahi et al., 2019). The proposed system does not correlate fuel consumption with load demand which contradicts the research finding. A cost-focused approach is prioritized overload management based on generated power in the proposed method. A particle swarm optimization algorithm-based energy management strategy is proposed by Peng et al. to address the power quality degradation and optimize energy management for fuel cell hybrid electric ships (Peng et al., 2023). The proposed energy management approach does not analyze its robustness and sensitivity to an extreme change in shipload at variable marine weather conditions including rough seas, high winds and other environmental factors. The proposed approach is unreliable for highly dynamic nonlinear marine loads due to the lack of performance validation, which compromises the analysis and results. For reducing fuel consumption and CO_2 emission of the electric ferry, a modified black hole algorithm (BHA) is proposed by Navid et al. This research used a d-Space real-time simulator for validating the proposed approach for improving the efficiency of the electric ferry (Vafam et al., 2020). This research emphasizes cost effective energy management approach rather than effective load management of the hybrid ferry. There is no relative comparison of the proposed optimization algorithm with other meta-heuristic optimization algorithms to justify its effectiveness in energy management.

Si et al. carried out a study on the multi-objective configuration optimization method (COM) and energy management strategy (EMS) for a ship based hybrid energy system based on quantum computing (Si et al., 2022). The EMS uses a mathematical model for a hybrid energy system and the objective function is optimized by a combination of fuzzy rules, quantum multi-objective artificial bee colony algorithm and multi-objective quantum particle swarm optimization algorithm (Si et al., 2022). Though the proposed method uses an advanced optimization algorithm, there is no indication of managing variable load which may hinder its robustness and appropriateness in practical application. The convergence problem of fuzzy logic may hamper optimization which is not considered in the study. Jianyun et al. presented an NSGA-II non-dominated sorting genetic algorithm for solving the multi-objective optimization problem (Cortés et al., 2010) of hybrid electric propulsive systems to optimize fuel consumption and GHG emission (Zhu et al., 2018). The performance test of the proposed method was conducted in real-time hardware in the loop system for a hybrid diesel-battery marine vessel (Daniel et al., 2023). The research focuses on optimizing fuel consumption and GHG emissions rather than on load management (Zhu et al., 2018). Martin et al. proposed an optimization approach for H_2 consumption to integrate proton exchange membrane fuel cells into lithium-ion batteries for replacing conventional internal combustion engine based marine power systems (Gay et al., 2022). The authors neither provide a clear and validated explanation of the power balance topology nor demonstrate the effectiveness of their method in comparison to other conventional power management approaches. A predictive energy management system is proposed by Planakis et al. which uses machine learning data from diesel generator driven ship operation for processing loading pattern according to marine loading cycles to manage a tradeoff between fuel consumption and NOx (nitrogen oxide) emissions minimization (Planakis et al., 2022). This research focuses more on keeping a tradeoff between fuel consumption and emission minimization rather than optimizing load demand according to generated power. The real time analysis of this research does not consider efficient load ship management which is the prime concern of any energy management system

Gao et al. introduced an adaptive equivalent consumption minimization strategy (A-ECMS) for hybrid electric ships (Gao et al., 2022). Their proposed approach extracts the optimal global equivalent factor trajectory from a dynamic programming (DP) solution and employs a back-propagation (BP) neural network to balance the trade-off between fuel consumption and battery aging (Gao et al., 2022). However, their objective function, which aims to minimize fuel consumption and battery aging, is not linked to load management, which is an important factor in real-time energy management for hybrid electric ships. Furthermore, the experimental results do not provide evidence to support the effectiveness of the proposed control strategy, raising doubts about its accuracy. Liu et al. proposed an energy control strategy for a hybrid electric ship that is based on minimizing the equivalent fuel consumption (Liu et al., 2021). They used an optimization function for efficient energy control to manage the power consumption of the battery power, optimizing the ship's energy control strategy (Liu et al., 2021). However, their proposed strategy does not prioritize load management control, which is a key aspect of real-time energy management for hybrid electric ships. The simulation results did not demonstrate the effectiveness of the proposed control strategy compared to other control topologies. The energy management strategy proposed by Chen et al. employs a support vector machine and frequency control based multi-objective optimization approach for a hybrid energy storage system, aiming to enhance power system dynamic performance and extend the fuel cell's lifespan (Chen et al., 2020b). Power management controllers based on simulated models may face limitations in adapting to system changes such as load demand fluctuations or changes in energy source availability, and may also lead to suboptimal control decisions due to inaccuracies in the representation of the real-world system. Rafiei et al. proposed and analyzed improved sine cosine optimization algorithm based energy management for a fuel cell and battery powered ferry which assessed the feasibility of the energy management system by using actual power dispatch data (Rafiei et al., 2020). The proposed approach does not consider the impacts of nonlinear dynamic ferry load on power management. The simulated analysis does not guarantee the application of the proposed system in real time due to a lack of performance validation.

The research works have been conducted on the PMS of marine vessels, most of them focusing on load management to improve fuel efficiency and storage SOC. Some of these studies have incorporated load forecasting approaches to managing fluctuating loads during severe sea weather conditions. However, most of these works have primarily concentrated on fuel consumption optimization rather than matching the load demand with the generated power. It is crucial to have appropriate load management in any PMS, which is dependent on the available generation to achieve the feasibility of the system. The efficiency of any PMS can only be achieved through proper balancing between the generated power and load demand, which has not been given much attention in previous research works (Rai, 2017). To address this gap, this research proposes a PMS for a fuel cell and storage battery powered electric ferry, using the load demand of a conventional ferry. The main objective of the proposed PMS is to optimize the dynamic load of the ferry with the generated power (Al-Falahi et al., 2018b). The proposed PMS adopts a two-stage power management strategy to optimize the H_2 fuel consumption and storage SOC by maintaining the optimal capacities of the fuel cell and BESS. The proposed meta-heuristic optimization algorithm and fuzzy logic control based PMS is validated by a simulated model. The validation results demonstrate the potential of the proposed two-stage power management strategy. This paper proposes a novel approach by prioritizing the proper matching of load demand with generated power to achieve optimal efficiency.

3. Methodology

The marine transportation industry is moving towards electric vessels powered by renewable energy sources such as fuel cells and storage batteries. The use of renewable energy sources and innovative power management strategies is an essential step towards a greener future for the marine transportation industry (Palconit and Abundo, 2018). However, the proper balance between generated power and load demand is crucial to the efficiency of any PMS, particularly for eco-friendly modes of transportation such as fuel cells and battery powered electric ferries (McKinlay et al., 2021; Kim et al., 2021). The importance of retaining the appropriate equilibrium between generated power and load demand of marine vessels for managing the efficiency of the proposed PMS has been overlooked in previous research works. To address this issue, this paper proposes a PMS for an electric ferry that runs on the fuel cell and BESS. The load demand of a conventional diesel generator powered ferry is used to design the PMS, aiming to optimize the ferry's dynamic load with the generated power (Al-Falahi et al., 2018b; Aarskog et al., 2020). The primary objective of the proposed PMS is to achieve a balance between the power generated and the load demand to enhance the system's efficiency. To achieve optimal balance, a two-stage power management strategy is proposed to optimize the H_2 fuel consumption and battery SOC. The PMS ensures that the optimal capacities of the fuel cell and BESS are maintained throughout the ferry's operation. The proposed PMS design aims to ensure maximum efficiency while minimizing the environmental impact.

The installation cost of fuel cells combined with BESS in electric ferries can be prohibitively high for owners and operators (Yuan et al., 2020). However, efficient load power management can offset the initial costs and make renewable-powered electric ferries a viable option in the marine industry. The efficiency of a fuel cell and BESS powered electric ferry's PMS relies on minimizing the fuel cell's H_2 consumption during cruising cycles (Xu et al., 2021). Maintaining the BESS SOC within specified limits when discharging to meet the ferry load, alongside the fuel cell, is crucial. The BESS is typically charged by a shore-side charging station to help the fuel cell manage the dynamic nonlinear ferry load (Kim et al., 2021). Once the ferry's load is met, the excess power generated by the fuel cell can be used to charge the BESS to its optimal SOC (Katzenburg, 2021). As ferries consume the most energy while cruising, the PMS for fuel cell and BESS operation must adequately support cruising cycles (Deshpande and Taylor, 2022). To ensure a long battery life, marine battery manufacturers suggest using an 80% maximum depth of discharge or a 20% minimum SOC which is used as a storage constraint for the proposed PMS (Malla, 2020). Appropriate optimization algorithms for fuel cell and BESS capacities should be implemented to match the load demand (Malla, 2020; Al-Falahi et al., 2019a). A sustainable and efficient transportation solution for the marine industry can be initiated by considering all the aspects of efficient power management.

To efficient management of electric ferry load by considering an optimal balance between load and generated power, a two-stage PMS has been proposed in this research (Kanellos et al., 2016). In the first stage of the proposed PMS, meta-heuristic optimization algorithms such as Particle Swarm Optimization (PSO), Bacterial Foraging Optimization (BFO), and a hybrid PSO-BFO algorithm are utilized (Kumar et al., 2020). These algorithms determine the optimal capacities of the fuel cell and BESS, taking into account the ferry's load demand and operational constraints such as fuel cell capacity and BESS SOC. The second stage of the PMS employs a Mamdani rule-based FLS to match the dynamic ferry load with the available power from the fuel cell and battery. The fuzzy logic system takes into account the load demand and generated power to ensure that the fuel cell operates at maximum efficiency while minimizing H_2 fuel consumption. The membership functions and fuzzy rules are selected based on the load profile and related constraints, which serve as input parameters for the optimization algorithm. Since the fuzzy logic does not ensure global stability, the membership functions and rules of the FLS are optimized by a hybrid PSO-BFO algorithm (Raju et al., 2019). The optimized FLC ensures efficient power management by matching the load demand and generated power, which leads to efficient power management of the electric ferry. In conclusion, the proposed two-stage power management system for electric ferries utilizes meta-heuristic algorithms and fuzzy logic to optimize load power management. The system can achieve efficient load management and ensure that the fuel cell and battery support the power demand of the ferry during cruising and loading and unloading at the berth. This approach offers a promising solution to the challenges of energy management in electric ferries and could pave the way for more sustainable and efficient maritime transportation in the future. Fig. 1 represents the schematic diagram of the proposed two stage PMS.

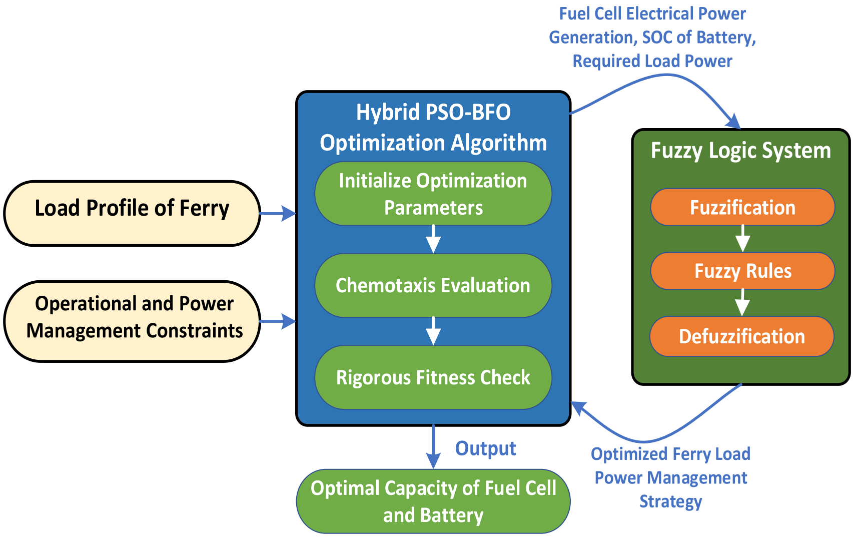

Fig. 1. Proposed load power management algorithm.

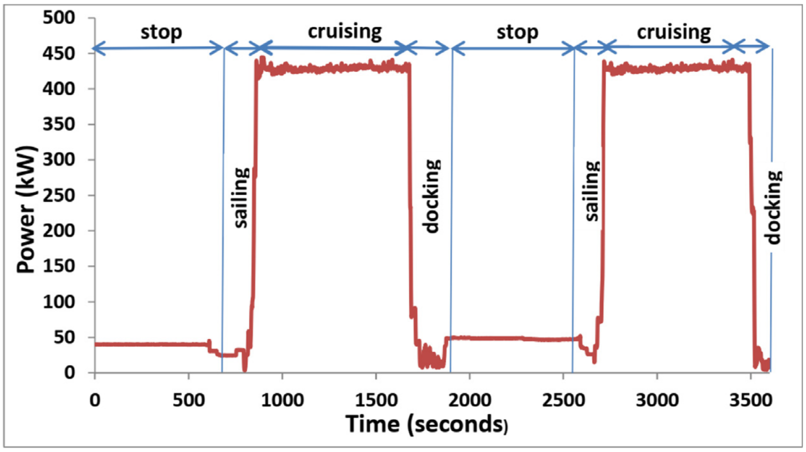

Fig. 2. Load profile of MV Bowen ferry.

4. Determining power sources capacities

The proposed PMS is designed for fuel cell and battery operated electric ferries. The capacities of the fuel cell and battery are determined according to load power consumption data of the MV Bowen short-haul ferry which operates between Kettering (Hobart) and Roberts Point (Bruny Island) (Al-Falahi et al., 2018). The Bowen ferry is equipped with two diesel engine generators with a capacity of 400 kVA (kilo volt ampere), covering a distance of approximately 6.2 km in a round trip that takes 60 min (Al-Falahi et al., 2018). The total energy consumption for a single round trip is 200.17 kWh (kilo watt hour) (Al-Falahi et al., 2018). Fig. 2 shows the load profile of the ferry, revealing that its power consumption ranges from a minimum of 3.44 kW to a maximum of 444.6 kW (kilo watt). This load capacity is used to determine the required capacities of the fuel cell and BESS for the proposed PMS.

4.1. Determining battery and fuel cell capacity

For calculating the battery capacity, conventional formulas are used (Al-Falahi et al., 2018; Palconit and Abundo, 2018).

$$E_B = \frac{E_L \times A \times B \times SOC}{1000} \tag{1}$$

Here, E_B is the battery capacity in kWh, A is the autonomy days which is considered as 1 day, E_L is the load demand in kWh, B is the backup hours which is 1 hour for a round trip and SOC is the state of charge in percentage.

$$E_B = \frac{N_S\left[E_T^{max} + E_C^{max}\right] + SOC_{min}\left[E_T^{max} + E_C^{max}\right]}{\eta_d} \tag{2}$$

Here, E_B represents the energy capacity in kWh whereas E_T^{max} and E_C^{max} represent the highest energy consumption of the ferry in kWh at berth and cruising respectively. The SOC_{min} is the minimum state of charge of the battery. The η_d is the discharging efficiency of the battery and N_S is the number of stops in a round trip.

The fuel cell capacity is determined by the conventional energy equation as follows (Liu et al., 2022; Tashie-Lewis and Nnabuife, 2021).

$$E_{FC} = \frac{Q \times V}{3.6 * 10^6} \tag{3}$$

Here, E_{FC} is the fuel cell capacity in kWh, Q is the quantity of electric charge for one hydrogen electron in coulombs and V is the fuel cell voltage in volts. The Q is generally represented by Eq. (4) (Liu et al., 2022; Tashie-Lewis and Nnabuife, 2021).

$$Q = n \times N_{avg} \times q_{el} \tag{4}$$

Here, N_{avg} = number of molecules per mole = $6.022 * 10^{23}$ molecules/mol, n = number of electrons per molecule of $H_2 = 2$ electrons/ molecule and $q_{el} = 1.602 * 10^{-19}$ coulombs/electron. The equation for determining the hydrogen quantity for the fuel cell can be represented (McKinlay et al., 2021) as,

$$H = \frac{P \times t \times 3600}{\eta \times LHV} \tag{5}$$

Here, H is the hydrogen amount in kg, P is the fuel cell capacity in kW, t is the time in an hour, η is the fuel cell efficiency in percentage and LHV is the lower heating value of hydrogen which is 120,000 kJ/kg.

4.2. Objective functions and optimization constraints

The objective of the proposed energy management system is the minimization of fuel content for the fuel cell-battery-operated electric ferry. Therefore, the objective of Eq. (6) is represented by using Eq. (5).

$$F = \frac{FC \times 3600}{w \times 1200000} \tag{6}$$

Here, F is H_2 content in kg which is the objective function, FC is the capacity of the fuel cell and w is the weight factor of the optimization algorithm.

The objective function indicates that minimizing fuel consumption is directly linked to optimizing the fuel cell's capacity. Similarly, the optimized capacity of the battery and its state of charge (SOC) plays a crucial role in managing the ferry's load demand. By varying the fuel cell capacity (FC) and battery SOC according to the load demand, the objective function can be expressed as follows (Dubuisson et al., 2020) to achieve the desired fuel consumption reduction.

$$\min_{x^L \in X^L, y^L \in Y^L} \sum_{L_{min}}^{L_{max}} \sum_{S_{min}}^{S_{max}} FC_{L,S}\,\omega(x_S^L - y_S^L) \tag{7}$$

Here, L and S represent the load demand and SOC which varies from maximum and minimum limit according to the operational data of the MV Bowen ferry. The ω is the weight factor of the optimization algorithm. The fuel cell capacity is a function of L and S. The variables, x_S^L and y_S^L are elements of operational vectors $X^L and Y^L$, whose difference can be represented by a new variable, $z_S^L = x_S^L - y_S^L$ which denotes the rate of variation of load and SOC with time. The vectors X^L and Y^L represent the constraint boundaries of the load demand of the ferry. The capacity of the fuel cell is constrained by the maximum and minimum load demand of the ferry which is expressed by Eq. (8) (Villamil et al., 2018). According to the load profile of the MV Bowen ferry, the maximum and minimum load demands are 444.6 kW and 3.44 kW respectively.

$$L_{min} \le FC_t^L \le L_{max} \tag{8}$$

The SOC of the battery is an important factor in supporting the load demand of the ferry. The SOC for a round trip of the ferry with time duration, t can be defined as (Villamil et al., 2018),

$$soc_t^L = soc_0^L + \Delta \sum_{t=1}^{t} \left(a_t^L - b_t^L\right) \tag{9}$$

Here, a_t^L and b_t^L are variables that depend on the change in load demand with time and Δ represents the time duration. The soc_0^L expresses the initial SOC and soc_t^L represents the variation of SOC with the change in load and time. To retain the longevity of the battery lifetime, the SOC needs to be within the permissible limit. Therefore the SOC should be constrained within boundary values which are shown in Eqs. (10) and (11) respectively (Villamil et al., 2018).

$$soc_l^L \le soc_t^L \le soc_u^L \tag{10}$$

$$soc_l^L \le soc_t^f + \Delta \sum_{t=1}^{t} \left(a_t^L - b_t^L\right) \le soc_u^L \tag{11}$$

Here, soc_u^L and soc_l^L are the upper and lower bounds of the battery SOC. The final SOC, soc_{ch}^L is constrained to the desired level of charging and discharging according to the load demand which can be represented by Eq. (12) (Villamil et al., 2018). The upper and lower bound of SOC are considered 100% and 20% respectively.

$$soc_{ch}^L = soc_0^L + \Delta \sum_{t=1}^{t} (a_t^L - b_t^L) \tag{12}$$

From Al-Falahi et al. (2019), it can be inferred that the SOC is a linear function of the charging/discharging rate, $c_t^L \approx a_t^L - b_t^L$ and storage constraints are dependent on that rate. For optimal power management of the ferry, the total available power from the fuel cell and battery must be equal to the load demand for a round trip. The balancing equation for power management can be expressed by Ramachandran (2011),

$$\sum_{t=1}^{t} (P_{FC,t} \times \exists + P_{B,t}) = P_{L,t} \tag{13}$$

Here, $P_{L,t}$ represents the load power in kW at time t, $P_{FC,t}$ represents the generated power of the fuel cell in kW at time t, $\exists$ is the operating variable of the fuel cell which can be 1 when the fuel cell is in operation and 0 when the fuel cell is not in operation and $P_{B,t}$ denotes the battery power in kW at time t. The $P_{B,t}$ can be either charging (negative value) mode or discharging (positive value) mode which depends on the load requirement of the ferry.

5. Proposed power management system design topology

The first stage of the proposed two stage power management system (PMS) involves determining the optimal capacities of the fuel cell and battery energy storage system (BESS) through the minimization of an objective function, specifically the H_2 fuel optimization. This is done in consideration of the variable load profile of the MV Bowen ferry. The proposed PMS involves a sophisticated optimization process that leverages different optimization algorithms such as Particle Swarm Optimization (PSO), Bacterial Foraging Optimization (BFO), and Hybrid PSO-BFO to determine the optimal capacities of the fuel cell and BESS.

Particle Swarm Optimization is a bio-inspired optimization algorithm that is considered one of the most powerful methods for resolving non-smooth global optimization problems (Lee and bae, 2006). It has been successfully applied in complex optimization problems in power systems. The PSO algorithm uses a simple technique to find an optimal solution in the search space (Lee and bae, 2006). It is a derivative-free method like other optimization algorithms, making it a powerful tool for solving non-smooth global optimization problems (Lee and bae, 2006). The PSO algorithm has a limited number of parameters, with only one inertia weight factor and two acceleration coefficients, making it more suitable than other meta-heuristic optimization algorithms (Lee and bae, 2006; Victoire and Jeyakumar, 2005). Moreover, the impact parameters of PSO are less sensitive to the objective function compared to conventional mathematical and other meta-heuristic optimization approaches (Gaing and Gaing, 2003). This is because most optimization approaches heavily rely on initial parameters, while the PSO algorithm is less

Algorithm 1: Pseudo code of PSO

```
Step 1: Initialization:
        i)   Find the initial population by clustering method
        ii)  Calculate the objective function of initial solutions (f)
        iii) Set initial velocity vector equal to zerosSet Pb = f, Gb = min(f); (Gb is Global best and Pb is
             Local best)
Step 2: Repeat the following steps until the stopping condition is met
        a)   Update Gb and Pb
             For i = 1: Ps (Ps = Population size)
                 If fi < Pb(i)
                         Pb(i) = fi
                 End
             End
             b = min (f) (b = best solution of current generation)
             If b < Gb
                 Gb = b
             End
        b)   Generate next population by using following equations ( x = position of particle, v = velocity of
             particle, w = weighting factor, r1 and r2 are random numbers, c1 and c2 are acceleration
             constants)
                 $\vec{v}(t+1) = \vec{v}(t) * w + \varphi_1 * \left(\vec{P_b}(t) - \vec{x}(t)\right) + \varphi_2 * \left(\vec{G_b}(t) - \vec{x}(t)\right)$
                 $\varphi_1 = r_1 * c_1$ and $\varphi_2 = r_2 * c_2$
                 $\vec{x}(t+1) = \vec{x}(t) + \vec{v}(t+1)$
        c)   Checking the feasibility of generated solutions and repair them by described strategy
        d)   Checking the objective function of generated solutions (f)
Step 3: Repeat the best solution
```

dependent on initial parameters, which generates robust convergence (Lee and bae, 2006). The use of the PSO algorithm is particularly effective due to its simplicity, easy implementation, robust convergence, and ability to provide high-quality solutions in a relatively short amount of time (Gaing and Gaing, 2003). In addition, the PSO algorithm is known to provide a high-quality solution with minimum calculation time and stable convergence characteristics, making it a better choice than other stochastic methods (Lee and bae, 2006; Victoire and Jeyakumar, 2005). The pseudo-code of the PSO algorithm is presented in Algorithm 1.

The Bacterial Foraging Optimization (BFO) algorithm is a population-based stochastic optimization technique that is widely used for the optimization of nonlinear functions in multidimensional space (Pareek et al., 2014). Its simplicity in structure, fast convergence speed, and high accuracy make it a suitable optimization algorithm compared to other meta-heuristic algorithms (Dubuisson et al., 2020; Chen et al., 2020). BFO's good performance in local search, self-resilience in searching activities, and derivative-free technique have made it a popular choice for solving optimization problems (Gan and Xiao, 2020). In certain situations, however, the BFO algorithm may converge slowly while maintaining high accuracy, which can be problematic for real-time applications (Gan and Xiao, 2020). To overcome this issue, researchers have proposed hybridizing the BFO algorithm with other optimization algorithms.

To improve the optimization results further, the PSO and BFO algorithms are often combined in a hybrid approach (Pattnaik et al., 2019). The PSO algorithm is known for its fast convergence, but this may come at the expense of accuracy (Pattnaik et al., 2019). On the other hand, BFO is a slow converging algorithm that provides better accuracy (Pattnaik et al., 2019; Kumar et al., 2019). Therefore, the hybridization of these algorithms allows for better accuracy in less time. In the hybrid PSO-BFO algorithm, the position of particles is updated using the respective local and global optimal solutions (Raju et al., 2019). The local solution is updated using the PSO algorithm, which speeds up the convergence of the BFO algorithm (Pattnaik et al., 2019). The PSO algorithm also controls the direction of bacteria in the BFO chemotaxis iteration for better convergence, which helps obtain the optimal solution in minimum operation time (Pattnaik et al., 2019; Kumar et al., 2019). The hybrid PSO-BFO algorithm utilizes the historical optimal solution for comparison with the bacteria populations' global optimal solution in BFO chemotaxis iteration (Kumar et al., 2019). This approach allows for faster convergence, leading to an optimal solution in less time. Overall, the hybrid PSO-BFO algorithm's use for optimizing the fuel cell and BESS capacities in the proposed PMS can provide a more accurate and faster optimization solution compared to using either algorithm alone. The BFO and hybrid PSO-BFO pseudo-codes are presented in Algorithms 2 and 3, respectively.

In the second stage of the PMS, the goal is to match the dynamic load of the ferry with the available power of the fuel cell and storage battery. To achieve this, a Mamdani rule-based fuzzy logic system (FLS) is used. In this system, the required load power consumption and battery state of charge (SOC) are taken as inputs, while the generated or output power of the fuel cell is taken as output. The optimized capacities of the fuel cell and BESS obtained in the first stage are used in the FLS for ferry load matching. To properly manage the ferry load, the storage capacity of the BESS needs to be synchronized with the ferry's required power. This helps the fuel cell to manage the ferry load effectively. Any excess power of the fuel cell after meeting the ferry load is used to charge the battery according to its SOC. This mechanism allows the BESS to manage the high load demand during cruising cycles in addition to the fuel cell.

The schematic diagram of the FLS is shown in Fig. 3. To define the membership functions of the required power (input) and output power (output), three membership functions are selected for each, including two trapezoidal and one triangular function. These membership functions are named low (trapezoidal), average or normal (triangular), and high (trapezoidal), as shown in Fig. 4. The value of the membership functions of the required power and output power is defined based on the maximum and minimum load power of the MV Bowen ferry which varies from 0 kW to 444.6 kW, while the membership functions of the battery SOC vary from 0 to 1 (0% to 100%). The range of the membership functions for inputs and output is presented in Table 1. Nine rules are selected for the FLS, which are presented in Table 2. The fuzzy rules match the required power of the electric ferry with the generated power of the fuel cell and BESS SOC. The fuzzy control parameters such as membership functions and rules are optimized using the hybrid PSO-BFO algorithm for optimal ferry load management. Overall, the second stage of the PMS is crucial in matching the dynamic load of the ferry with the available

ALGORITHM 2: PSEUDO CODE OF BFO

```
Step 1: Initialize the BFO parameters,
        N: Total bacteria
        Nc: Count of Chemotaxis steps
        Nre: Total reproductive steps
        N: Dimensions of the problem
        C: Step size taken by tumble
Step 2: For every reproduction step perform the following
Step 3: For every chemotaxis step perform the following
        i)   calculate the fitness function(J) of the initial population using the equation,
                 $X_i(i+1) = X_i(i) + V_i(i+1)$
        ii)  set Jlast = J. Hold this vale and a better cost value via a swim can be found
        iii) Tumble: Create a random vector delta from -1 to 1
        iv)  Move: Let move the bacterium to a position with step size C(i) using the below equation called
             Tumble.
                 $del = (rand(1,1) - 0.5) * 2$
                 $X(i+1) = X(i) + C(i)\frac{Del(i)}{Del(i)Del^T(i)}$
        v)   Again swim
             a) Let m = 0
             b) While m < Ns ( not climbed too much)
             c) m = m+1;
             d) If J(i) > Jlast ( if present is better than previous)
             e) Let Jlast = J(i) and use this Jlast to calculate the new J
                    $X(i+1) = X(i) + C(i)\frac{Del(i)}{Del(i)Del^T(i)}$
             f) Else, calculate the new J using the following equation
                    $X_i(i+1) = X_i(i) + V_i(i+1)$
                For m = Ns; end of the while loop
             g) Go to next bacterium i.e. go to the (i) step to calculate for the next bacteria
Step 4: End of Chemotaxis loop? If No, repeat Step 3
Step 5: Begin reproduction loop
             a) Calculate the health of each bacterium by finding the maximum cost value of each bacterium
             b) The bacterium with the lowest $J_{health}$ ( final fitness) values will die and the remaining bacteria
                with the best fitness values are split into two bacteria thus making population of bacteria
                constant
```

Table 1
Range of membership functions for inputs and output.

Membership function	Required power (kW)	SOC	Output power (kW)
Low (trapezoidal)	[0,0,88.92, 222.3]	[0,0,0.3,0.5]	[0,0,88.92, 222.3]
Average/Normal (triangular)	[88.92,222.3, 322.3]	[0.4,0.5,0.6]	[133.4,222.3, 289]
High (trapezoidal)	[222.3,322.3,444.6,444.6]	[0.5,0.7,1,1]	[222.3,311.2, 444.6,444.6]

Table 2
Mamadani rule-based fuzzy logic.

Fuzzy logic			
Rule No.	Ferry required power	Battery SOC	Fuel cell output power
1	High	Low	High
2	High	Normal	High
3	High	High	Low
4	Average	Low	High
5	Average	Normal	Average
6	Average	High	Low
7	Low	Low	Average
8	Low	Normal	Low
9	Low	High	Low

power of the fuel cell and storage battery. The FLS, along with the optimized capacities of the fuel cell and BESS, ensures that the ferry load is managed effectively, and any excess power is stored in the battery for later use.

6. Performance results and validation

To reduce the computational burden of the optimization algorithms (Kumar et al., 2019), a maximum iteration of 20 is considered to obtain the optimal capacities of the fuel cell and BESS, along with the optimal consumption of H_2 fuel using PSO, BFO, and hybrid PSO-BFO algorithms (Pattnaik et al., 2019). The optimal values obtained through these algorithms are presented in Table 3. The optimal capacities of the fuel cell are 315.97 kWh, 317.96 kWh and 318 kWh while the optimal capacities of the BESS are 314.89 kWh, 316.97 kWh and 317.64 kWh respectively for PSO, BFO and hybrid PSO-BFO algorithms respectively. It can be observed that the hybrid PSO-BFO algorithm (Raju et al., 2019) provides the best optimized values. Fig. 5 illustrates the optimal capacities of the fuel cell and BESS obtained using the hybrid PSO-BFO algorithm at various iterations. It is evident from the figure that the optimized values converge to a stable point after a few iterations. The minimization of the objective function indicates that the fuel cell requires approximately 18 kg of H_2 fuel to generate power and meet the ferry load during cruising cycles. The ferry load demand is managed by the FLS by considering the available power from the fuel cell and BESS. The fuzzy control parameters of the FLS are optimized by the PSO-BFO algorithm to ensure the matching between inputs and output (Mimica, 2022). The optimized fuzzy control parameters are depicted in the fuzzy logic rule viewer of Fig. 6. For any required load power of 224 kW, the output generated power of the fuel cell is 220 kW and the BESS SOC is 0.5.

The relationship between the input and output parameters of the FLS is demonstrated graphically in Fig. 7. To evaluate the effectiveness of the proposed PMS, a fuel cell and BESS powered ferry model is developed in Matlab Simulink, as shown in Fig. 8 (Hou et al., 2018). The optimal capacities of the fuel cell and BESS obtained by the PSO-BFO algorithm are used in the simulated model (Hou et al., 2018). The PSO-BFO optimized FLS is represented by the controller block. The simulation result shows that the proposed PMS is capable of balancing the ferry load demand by effectively utilizing the available power of the fuel cell and BESS, as shown in Fig. 9. The PSO-BFO optimized FLS

ALGORITHM 3: PSEUDO CODE OF HYBRID PSO-BFO

```
Step 1: Set the BFO parameters,
        N: Total bacteria
        Nc: Count of Chemotaxis steps
        Nre: Total reproductive steps
        N: Dimensions of the problem
        C: Step size taken by tumble
        ω: The inertia weight
        CI: swarm confidence
        X(i): Location of the ith bacterium
        V(i): Velocity of the ith bacterium
        Gbest: Global best position value
        Pbest: Local best position value
Step 2: Start elimination of dispersal loop
Step 3: For every reproduction step, perform the following
Step 4: For every chemotaxis step, perform the following
        i)   calculate the fitness function(J) of the initial population using the equation,
                 $X_i(i+1) = X_i(i) + V_i(i+1)$
        ii)  set $J_{last}$ = J. Hold this vale and a better cost value via a swim can be found
        iii) Tumble: create a random vector delta from -1 to 1
        iv)  Move: Let move the bacterium to a position with step size C(i) using the below equation called
             Tumble.
                 $del = (rand(1,1) - 0.5) * 2$
                 $X(i+1) = X(i) + C(i)\frac{Del(i)}{Del(i)Del^T(i)}$
        v)   Again swim
            c) Let m = 0
            d) While m < Ns ( not climbed too much)
            e) m = m+1;
            f) If J(i) > $J_{last}$ ( if present is better than previous)
            g) Let $J_{last}$ = J(i) and use this $J_{last}$ to calculate the new J
                   $X(i+1) = X(i) + C(i)\frac{Del(i)}{Del(i)Del^T(i)}$
            h) Else, add a new random number and calculate
                   new J(i)
                   let m = Ns;
                   end ( while statement)
Step 5: Mutation (by PSO operator)
        For i= 1, 2, .........., S
        Initialize the Gbest and Pbest
        Update the position and velocity of the i-th bacterium using the following equations
            $V_i(i+1) = \omega V_i(i) + C1\varnothing 1(Pbest - x(i)) + C2\varnothing 2(Gbest - x(i))$
            $X_i(i+1) = X_i(i) + V_i(i+1)$
Step 6: Let Sr = S/2
The bacteria with the lowest $J_{health}$ (final fitness) values will die and the remaining bacteria with the best
fitness values are split into two bacteria this making the population of bacteria constant.
```

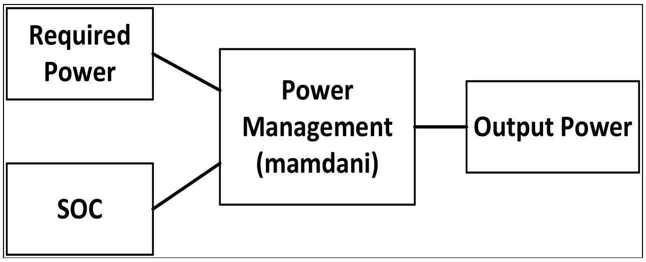

Fig. 3. Mamdani rule based FLS.

ensures that the load power consumption and battery SOC are considered as inputs and the generated power of the fuel cell is taken as output. This approach enables the fuel cell to manage the ferry load properly by matching it with the available power of the fuel cell and BESS. The excess power generated by the fuel cell is used to charge the battery, which assists in managing the high load demand during cruising cycles. The simulation result confirms that the proposed PMS can balance the ferry load demand, effectively utilizing the available power of the fuel cell and BESS, while minimizing fuel consumption.

Table 3
Optimal capacities of fuel cell, BESS and H_2 Intake.

Optimization algorithm	Fuel cell capacity (kWh)	BESS capacity (kWh)	H_2 fuel Intake (kg)
PSO	315.97	314.89	18.7
BFO	317.96	316.97	18.6
Hybrid PSO-BFO	318	317.64	18

7. Limitation of the proposed system and future work

The proposed PMS is considered for an electrical ferry with the fuel cell and BESS as power sources. The fuel cell and BESS may meet the dynamic load demand of the electric ferry but for large marine vessels, hybridization of renewables with conventional diesel generators can be a feasible option. The power management topology of multiple energy sources based hybrid marine vessels is not considered in this research work. The power management approach of marine vessels during abrupt fluctuations in load demand due to rough seas or extreme weather conditions is not considered in the proposed PMS. The PMS needs

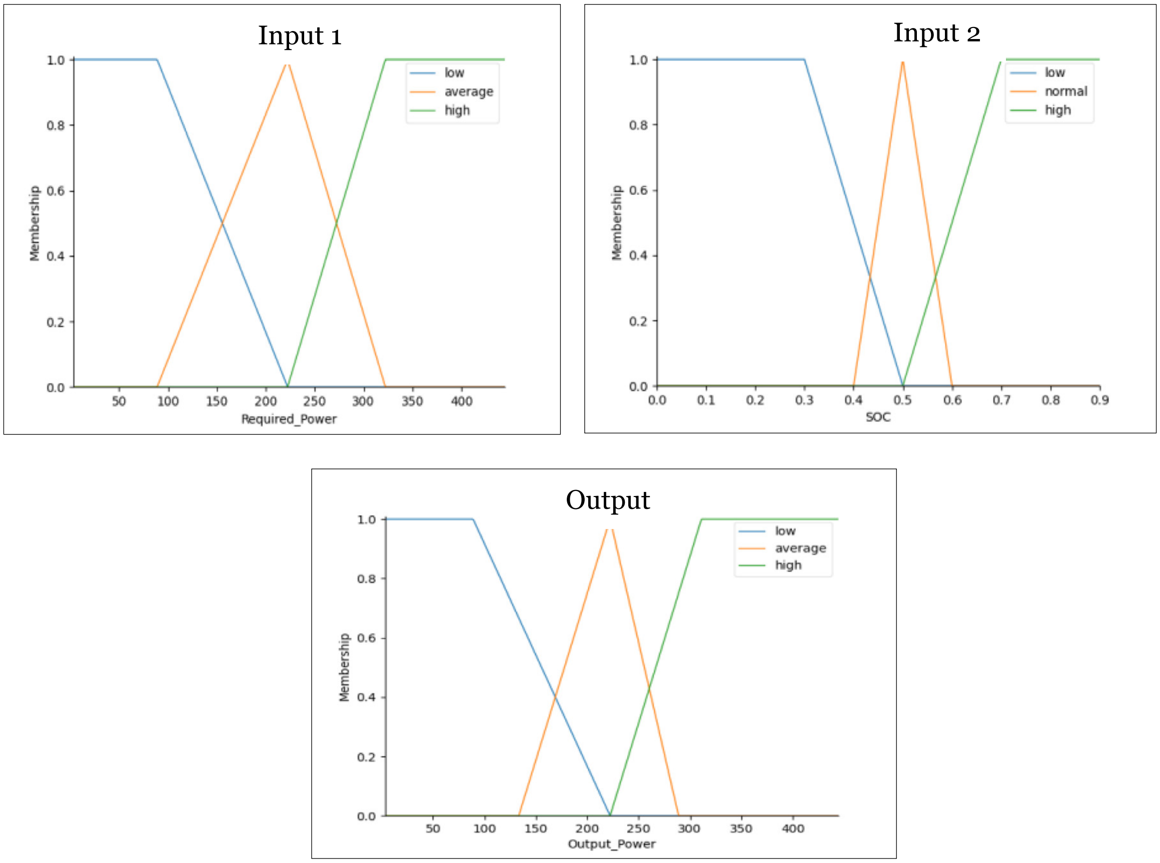

Fig. 4. Membership functions of inputs and output of FLS.

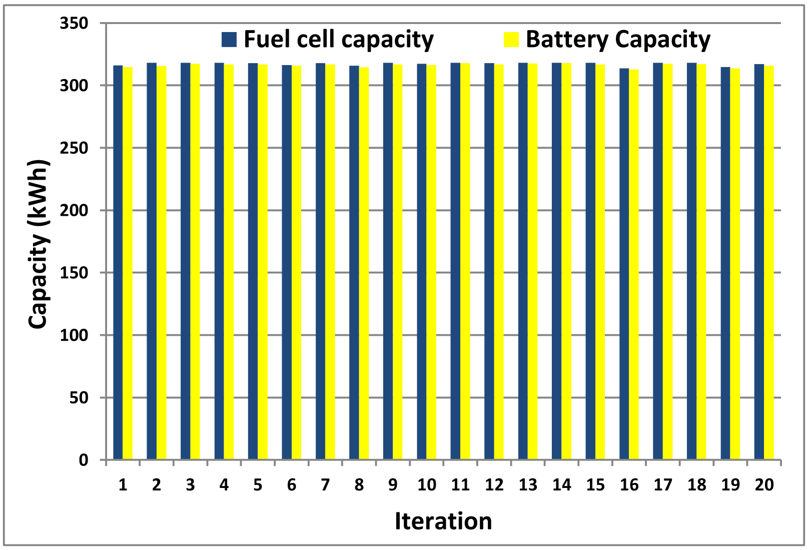

Fig. 5. Optimal capacities of fuel cell and BESS by hybrid PSO-BFO.

to operate in highly variable marine weather conditions including rough seas, high winds and other environmental factors. The proposed PMS does not analyze its robustness and sensitivity at an extreme change in electric ferry load. Not considering the complexity and nonlinearity of marine vessel power systems due to the integration of renewable sources and power electronics devices is a limitation of the proposed PMS. To address these challenges, the PMS in marine vessels needs to be highly adaptable and responsive which requires sophisticated control systems that can quickly manage the variable load according to the available generated power.

This research work mostly focuses on simulation based design topology and constraints of the proposed PMS for renewable energy powered electric ferry. Simulated model based PMS may be limited in their ability to adapt to changes in the system, such as changes in the load demand or availability of energy sources. The validation results for the simulation model based approach may not exactly match the real time results of the proposed PMS. The simulation results may not accurately capture

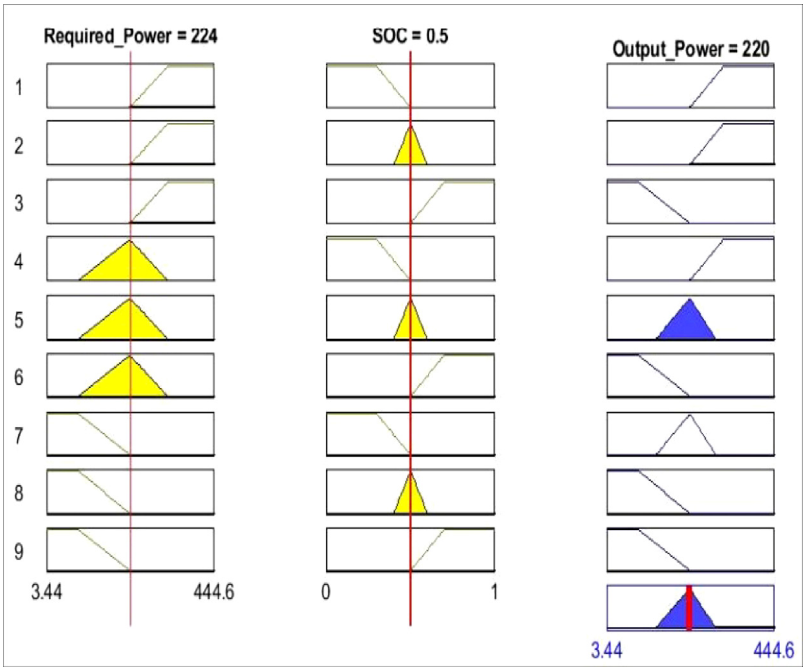

Fig. 6. Fuzzy logic rule viewer.

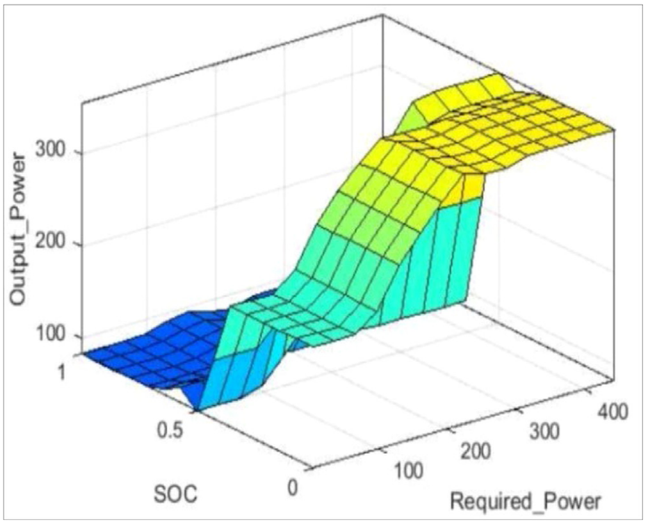

Fig. 7. Relation between input and output parameters of FLS.

the behavior of real-world systems, leading to inaccuracies in the power management control of the electric ferry. This research does not consider the capacities and connectivity of the converter, inverter, switchgear, cable, wire and other equipment of the electric ferry. To design the optimal overall electrical system of the ferry, other electrical equipment needs to consider which will be done in future research. There is a provision for upgrading the proposed PMS which will overcome the limitations of the current design topology. Future research will emphasize designing robust, reliable and adaptable PMS which will manage dynamic marine vessel load with respect to the nonlinear and intermittent power sources. The real time performance analysis will be included in future work to justify the accuracy of the simulation analysis. The elaborated performance analysis will assist in determining the applicability of the proposed PMS in the real world.

8. Conclusion

Marine vessels are a significant source of greenhouse gas emissions, but replacing conventional diesel engines with renewable sources can help mitigate environmental pollution. Solar PV, fuel cells, super-capacitor, and battery-based alternative electricity sources are gaining attention from ferry owners and operators. The fuel cell combined with a storage battery is a promising alternative to conventional diesel generators for small marine vessels such as electric ferries. However, the cost of alternative energy sources is still high compared to conventional fuel, which emphasizes the importance of reducing renewable fuel content and implementing efficient electrical power management in marine vessels. This research proposes a two-stage optimal power management approach to meet the load demand of a short-haul ferry while minimizing fuel consumption. The approach addresses electricity source, load, and storage constraints using PSO, BFO, and hybrid PSO-BFO optimization algorithms and a Mamdani rule-based fuzzy logic system. The optimization algorithms determine the optimal capacities of the fuel cells and batteries, while the fuzzy logic system ensures efficient load management that satisfies the objective of minimizing H_2 fuel content. The simulation results reveal that the hybrid PSO-BFO algorithm generates the best optimization capacities for the fuel cell and BESS with optimal H_2 intake to meet the load demand during cruising cycles. This simulation based research mainly focuses on optimizing alternative electricity generation sources for optimal power management in renewable sources powered marine vessels which can mitigate greenhouse gas emissions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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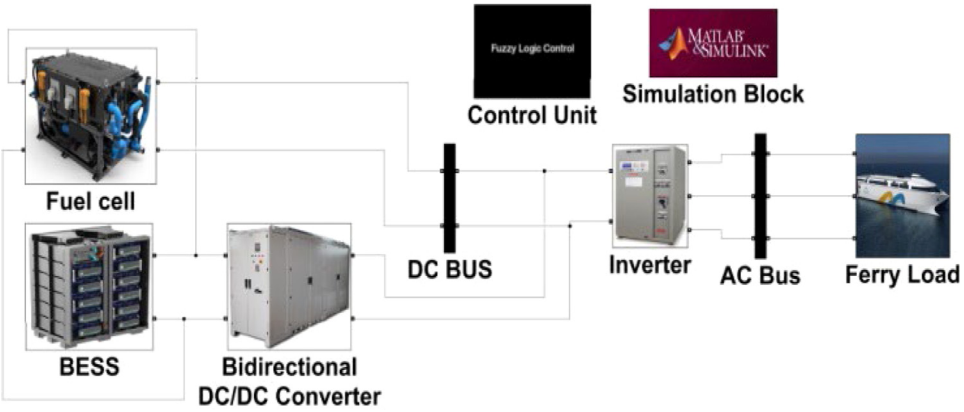

Fig. 8. Simulated model of ferry power management system.

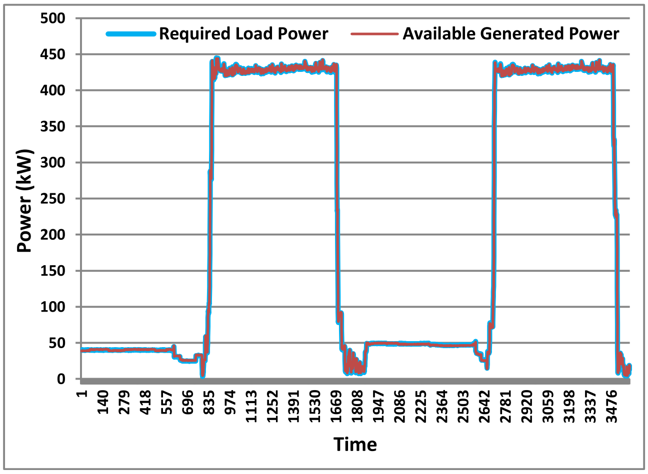

Fig. 9. Balance between load power and generated power.

Data availability

Data will be made available on request.

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