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STRATEGIC LOAD FLOW ASSESSMENT FOR A SHIP MICROGRID WITH PHOTOVOLTAIC POWER INTEGRATION

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Ships are one of the primary modes of transportation used worldwide. The Possibility of the extinction of fossil fuels soon, combined with the urge to reduce pollution, makes it necessary to use renewable energy as an inevitable source. To enhance air quality, it is imperative to minimize CO_2 emissions. It is essential to use a clean energy source to reduce carbon emissions. The key objective is to promote clean and green energy for transportation. Major contributors to global warming are the combustion of fossil fuels. This paper proposes utilizing solar energy on ships to generate electricity, thereby enhancing reliability and sustainability. In this work, a primary load flow analysis of an 18-bus shipboard electrical network is conducted using MATLAB/Simulink. Results obtained from load flow analysis are used to design a solar photovoltaic Panel based on the load requirements. This model enhances the efficiency and reliability of the ship's power system to supply all electrical loads on board.

1. INTRODUCTION

One of the primary means of transportation used worldwide is ships. Non-renewable energy sources, such as fossil fuels, are used as fuels in ships to a greater extent. This causes many ecological problems to the environment, such as global warming, air and water pollution. Carbon dioxide (CO_2) emissions originating from ports and ships have an influential impact on global warming [1]. Hazardous gases like nitrogen, Sulphur, CO_2, and hydrocarbons have been discovered, and ocean-going ships are the major contributors to pollution in the marine environment [2]. The marine and shipping sectors are experiencing an increasing need for ecologically sustainable ships due to more demanding ecological standards[3]. To further decrease reliance on fossil fuels, shipboard electrical systems have incorporated photovoltaic generators to reduce the use of conventional energy sources [4]. Standalone renewable energy systems consider solar, wind, and hydro resources, all of which are inherently boundless in nature, and serve as a viable alternative to grid-connected systems.[5].

The solar photovoltaic ship, an energy-efficient and environmentally friendly vessel, is becoming increasingly promising and rapidly evolving. The Generator's output power will be reduced proportionally by supplying the load through the transformed electric energy from the PV system via the ship's distribution system [6]. The utilisation of renewable energy is being enhanced for two primary reasons: economic, as a response to rising fuel costs, and environmental, to decrease hazardous emissions from ships[7]. A Shipboard Power Network is a standalone, small-scale electrical network that supplies electricity to the propulsion engine and services all types of loads on a ship, apart from traditional terrestrial power networks [8]. Improving the ship power network requires power management methods and design for ship power systems. These systems encompass the generation, conversion, distribution, protection, and consumption of energy [9].

Additionally, there is a pressing need to transition towards carbon-neutral fuels to safeguard our planet. Nevertheless, zero-carbon fuels are still in the early stages of development in the global shipping industry, and several perspectives and projections exist regarding the production, distribution, and consumption of these fuels to promote a sustainable maritime economy [10]. Solar energy is the optimal choice for energy use in the marine ecosystem due to its clean and abundant nature. The reasons for selecting solar energy as a replacement energy source in marine industries include zero pollution, high reliability, elimination of hazardous byproducts, lower power costs compared to stored energy from the grid, reduced ship weight, longer lifespan, and safer operation. It also proposed that using solar energy adds the advantage of instant power availability without a time delay in starting the engine, and an emergency stop is also possible [11,12]. The primary findings are highlighted in consideration of the research limitations identified in the literature review.

Key points

- In the present work, solar energy is utilized as the primary source of energy, which ultimately reduces the fuel carried by ships, thereby reducing the ship's weight.
- This work enhances the efficiency of the shipboard power system.

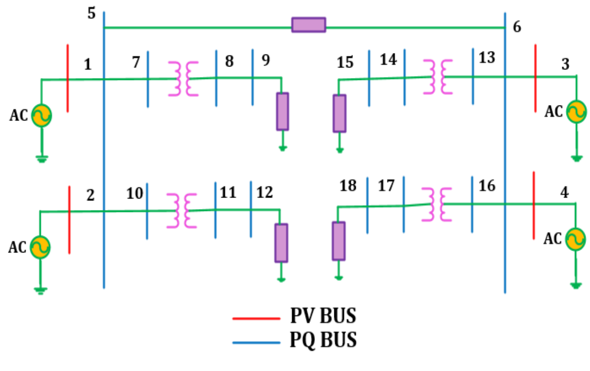

Fig 1 – Eighteen bus ship radial network.

Due to the continual advances in technology and the increasing worldwide emphasis on sustainability, the maritime industry is projected to maintain its shift towards hybrid power systems. Hybrid power systems offer numerous benefits; however, combining various energy sources can lead to complex power flow scenarios and necessitate harmonization among multiple energy providers [13].

2. ANALYSIS OF ELECTRICAL SHIP NETWORK

The PV-electric ships operate using electricity generated by

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the PV systems installed on board, as well as from the grid in case the PV systems are insufficient to meet the power need[10]. Baldwin and Lewis [14] examined 18 bus ship electrical radial networks. This ship line and bus data are taken for implementing this work. A load flow analysis of an 18-bus radial ship electrical network is performed in MATLAB/Simulink, which provides the load requirements of the ship.

2.1 SPECIFICATION OF 18 BUS SHIP NETWORK

The present work analyses the 18-bus ship electrical network which consists of four generators, six loads and four transformers as depicted in Fig. 1 reliant on the branch and bus data provided in Butler [15]. Figure 2 illustrates the Branch data for 18 Bus Ship Electrical Network. Four generators are

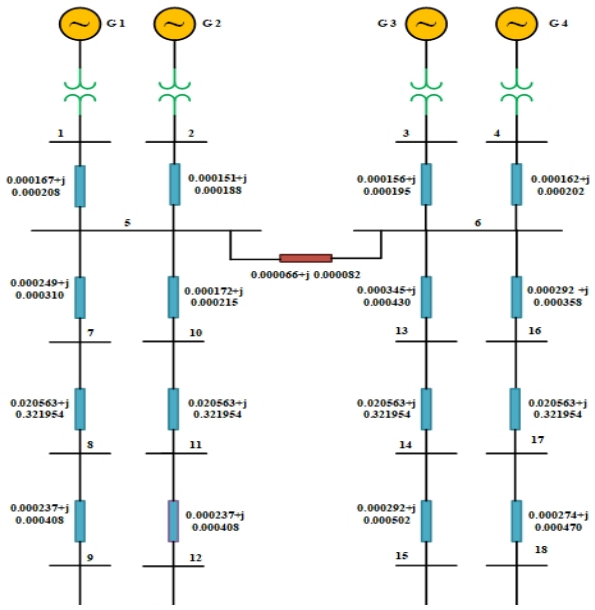

Fig 2 – Branch data of 18 bus ship.

connected to the buses 1, 2, 3, 4. Transformers are connected between the buses 7-8, 10-11, 13-14, 16-17 with tapping ratio 1 and six loads are connected to the buses 5, 6, 9, 11, 15, 18. First bus is taken as slack bus. In this network, primary power source is four generators connected to buses 1, 2, 3 and 4. There are three Generator buses and fourteen load buses. Modelling is carried out with 10 MVA base power and 6600 V of generation voltage. The Root means square voltage level of the network is 4760V. Tie line branch is 5-6. This network This network has four similar branches 9-7, 10-12, 13-15 and 16-18. The Branch data of 18 Bus ship network is depicted in Fig. 2. The Bus data of 18-bus ship electrical network is tabulated in Table 1.

Table 1.

18 bus ship branch data

Bus	Type	Voltage (P.U)	Generation (MW)	Load, P(MW)	Load, Q(Mvar)
1	Slack	1.02	Slack	0.00	0.00
2	PV	1.02	6.15	0.00	0.00
3	PV	1.02	6.04	0.00	0.00
4	PV	1.02	6.06	0.00	0.00
5	PQ	-	-	0.42	0.31
6	PQ	-	-	0.38	0.29
Bus	Type	Voltage (P.U)	Generation (MW)	Load, P(MW)	Load, Q(Mvar)
7	PQ	-	-	0.00	0.00
8	PQ	-	-	0.00	0.00
9	PQ	-	-	5.72	0.12
10	PQ	-	-	0.00	0.00
11	PQ	-	-	0.00	0.00
12	PQ	-	-	5.76	0.00
13	PQ	-	-	0.00	0.00
14	PQ	-	-	0.00	0.00
15	PQ	-	-	5.68	0.11
16	PQ	-	-	0.00	0.00
17	PQ	-	-	0.00	0.00
18	PQ	-	-	5.81	0.14

3. MATHEMATICAL MODELLING OF SHIP MICROGRID

3.1 POWER FLOW MODELLING

The Newton-Raphson method was employed for load flow analysis in ship network. This method offers a faster load flow analysis solution comparing with other methods [16]. For the power system with h bus, the Real and reactive power of the load buses are evaluated using the following mathematical equation [17],

$$P_a{}^{cal} = \sum_{b=1}^{h} V_a V_b Y_{ab} \cos(\theta_{ab} - \delta_a - \delta_b). \qquad (1)$$

$$Q_a{}^{cal} = -\sum_{b=1}^{h} V_a V_b Y_{ab} \sin(\theta_{ab} - \delta_a - \delta_b). \qquad (2)$$

where $P_a{}^{cal}$ implies Real power calculated, $Q_a{}^{cal}$ implies Reactive power calculated, V_a is the Voltage at bus a and V_b denotes Voltage at bus b.

The Jacobian matrix that includes real and reactive power derivatives can be efficiently computed as[18]

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix}. \qquad (3)$$

where J_1, J_2, J_3, J_4 are the Jacobian matrix coefficients. The Load flow equations denoted is computed iteratively employing the following procedures[18]

$$\delta^{m+1} = \delta^m + \Delta\delta. \qquad (4)$$

$$V^{m+1} = V^m + \Delta V. \qquad (5)$$

When the voltage and phase angle changes are under the predefined limit, the iterations of step m are terminated. Initially an optimal region for placing the solar array is identified based on the specifications of the PV system. Eventually, the total power supply from the solar PV system is estimated according to the trajectory of the Ship. The

$$PV_m = P_r \times n \qquad (6)$$

analysis concludes by examining the fuel-saving and lower emissions achieved through the renewable generation of power[19]. The generated peak power of solar panel is [19]. Here PV_m is the Solar PV Peak Power, P_r is Rated PV Power and n denotes Number of Solar panels.

Fuel saving of the PV powered ship and Emission Reduction can be calculated as

$$F_S = PV_m \times SFOC. \qquad (7)$$

$$E_r = E_f \times PV_m. \qquad (8)$$

where F_S is the Fuel savings, $SFOC$ is the Fuel Oil consumption, E_r is the emission reduction and E_f denotes emission factor.

4. POWER FLOW ANALYSIS

In a balanced three-phase system, the load flow analysis often relies on a steady-state condition [20]. Load flow analysis evaluates the balanced operating conditions of the 18-bus radial network using the provided branch and bus data. This information helps minimize losses and maintain system stability. The Newton-Raphson load flow method yields more reliable results than any other power flow solution method, based on convergence rate, iteration count, and memory usage, for an 18-bus radial ship electrical system shown in Fig. 1, which is implemented in MATLAB. It takes four iterations to converge. It is used as a reference for the load flow solutions of MATLAB/Simulink. Load flow solutions and line flow losses are tabulated in Tables 2 and 3, respectively. Load flow analysis is done in MATLAB and on a network. Power flow analysis of an 18-bus ship network. The process flow is shown in Fig. 3.

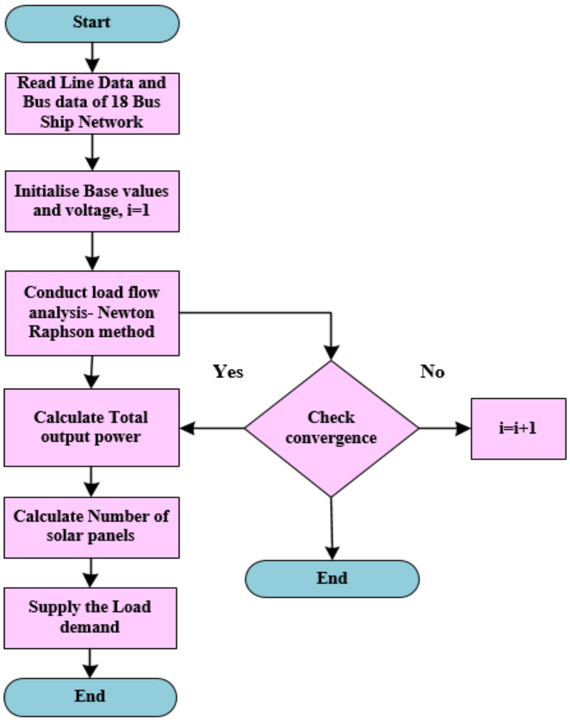

Fig 3 – Load flow analysis flowchart.

Table 2

Power flow solution by the N-R method.

Bus	Voltage	Angle	Load		Generation	
	(V)		MW	Mvar	MW	Mvar
1	1.02	0	0	0	5.81	1.218
2	1.02	0	0	0	6.15	1.567
3	1.02	0	0	0	6.04	1.447
4	1.02	0	0	0	6.06	1.202
5	1.02	-0.006	0.42	0.31	0	0
6	1.02	-0.005	0.38	0.29	0	0
7	1.02	-0.14	0	0	0	0
8	0.98	-10.53	0	0	0	0
9	0.98	-10.54	5.72	0.12	0	0
10	1.02	-0.011	0	0	0	0
11	0.98	-10.6	0	0	0	0
Bus	Voltage	Angle	Load		Generation	
			MW	Mvar	MW	Mvar
12	0.98	-10.61	5.76	0.09	0	0
13	1.02	-0.017	0	0	0	0
14	0.98	-10.46	0	0	0	0
15	0.98	-10.47	5.68	0.11	0	0
16	1.02	-0.015	0	0	0	0
17	0.98	-10.71	0	0	0	0
18	0.98	-10.73	5.81	0.14	0	0
Total loss				23.77	1.06	24.06

Table 3

Line flow losses.

Line		Bus Power and Line flow		Line loss	
From	To	MW	Mvar	MW	Mvar
1		5.808	1.218	5.935	
	5	5.808	1.218	5.935	0
2		6.15	1.567	6.347	
	6	6.15	1.567	6.347	0
3		6.04	1.447	6.211	
	6	6.04	1.447	6.211	0
4		6.06	1.202	6.178	
	6	6.06	1.202	6.178	0
5		-0.42	-0.31	0.522	
	1	-5.81	-1.22	5.934	0
	2	-6.15	-1.57	6.346	0
	6	-0.09	0.083	0.119	0
	7	5.791	1.204	5.915	0
	10	5.831	1.187	5.951	0
6		-0.38	-0.29	0.478	
	3	-6.04	-1.14	6.21	0
	4	-6.06	-1.2	6.177	0
	5	0.085	-0.08	0.119	0
	13	5.75	1.178	5.87	0
	16	5.884	1.262	6.017	0
7		0	0	0	
	5	-5.79	-1.2	5.914	0
	8	5.79	1.203	5.914	0.07
8		0	0	0	
	9	5.721	0.121	5.722	0
	7	-5.72	-0.12	5.722	0.07
9		-5.72	-0.12	5.721	
	8	-5.72	-0.12	5.721	0
10		0	0	0	
	5	-5.83	-1.19	5.95	0
	11	5.831	1.186	5.95	0.07
11		0	0	0	
	12	5.761	0.091	5.762	0
	10	-5.76	-0.09	5.762	0.07
12		-5.76	-0.09	5.761	
	11	-5.76	-0.09	5.761	0
13		0	0	0	
	6	-5.75	-1.18	5.868	0
	14	5.749	1.177	5.868	0.07
14		0	0	0	
	15	5.681	0.112	5.682	0
	13	-5.68	-0.11	-5.68	0.07
15		-5.68	-0.11	5.681	
	14	-5.68	-0.11	5.681	0
16		0	0	0	
	6	-5.88	-1.26	6.016	0
	17	5.883	1.261	6.016	0.07
17		0	0	0	
	18	5.811	0.142	5.813	0
	16	-5.81	-0.14	5.813	0.07
18		-5.81	-0.14	5.812	
	17	-5.81	-0.14	5.812	0

5. MODELLING OF SOLAR PV-POWERED SHIP

Han [21] said that the use of fossil fuels in the shipping sector affects the ecosystem. He proposed using renewable energy sources in the shipping sector. Thus, this proposed approach enhances the reliability of the network and increases the system's efficiency. Hussein [22] and Ioannis [23] also said that PV technology is a cost-effective solution for the shipping industry. Yan [24] noted that the fuel consumption of diesel engines is reduced because of the use of solar energy in ships. Kurniawan [25] also mentioned that the use of non-conventional energy reduces ship operation costs due to the uncertain price of oil. It has no rotating parts like a wind turbine, which may affect ship stability.

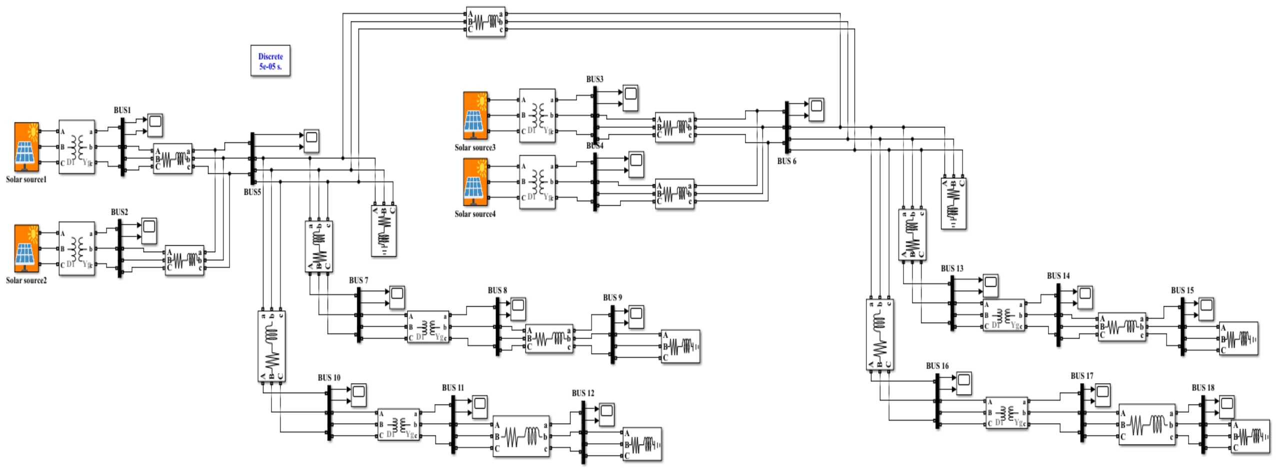

Fig. 4 – Photovoltaic ship modelling in MATLAB/Simulink.

The quantity of solar irradiance significantly influences the power output from photovoltaic systems [26]. Based on Villalva [27], a photovoltaic panel is modelled in MATLAB/Simulink. The sudden change in load can be met by modifying the number of cells connected in series and parallel. The power management of an electric ship involves defining the optimal quantity of electrical power that should be available consistently and maintaining a balanced distribution among the generators. The primary objective of power management under unfavourable circumstances is to provide a required amount of power to ship essential loads. Effective scheduling of power-generating units based on system demand enables the most efficient use of fuel, resulting in high efficiency [28]. Figure 4 represents the modelling of the 18-bus radial network in MATLAB/Simulink.

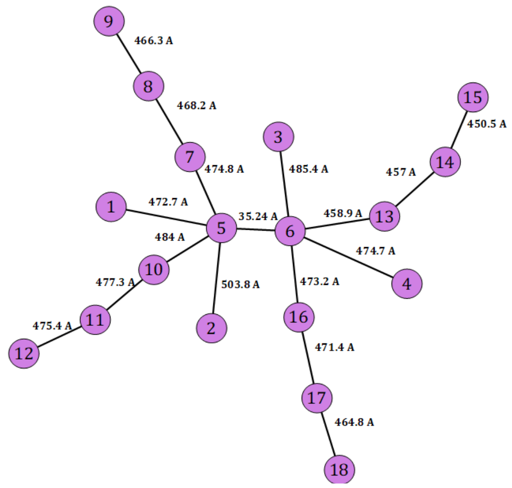

Fig. 5 – Current profile of ship network.

To enhance the realistic application of the proposed simulation approach, the 18-bus shipboard electrical system created in this study is designed to match the setup of a modern all-electric ship. Bus 1 serves as the slack bus, representing the main distribution switchboard. Buses 2, 3, and 4 are modeled as PV buses, corresponding to three onboard diesel generators. The remaining buses, numbered 5 to 18, are classified as PQ buses, which represent the electrical needs of essential ship systems. These systems include engines, navigation and communication tools, heating and lighting, kitchen and living area services, extra machinery, and backup systems. This configuration effectively captures the radial medium-voltage distribution structure that is typical of marine power systems. Load profiles were assigned to these buses to simulate realistic operational modes, including port stay, maneuvering, and cruising. These adjustments ensure that the simulation reflects not only the theoretical flow of power but also the dynamic situations encountered during actual ship operations. This enhances the model's accuracy and its usefulness for analyzing operations and managing energy.

6. RESULTS AND DISCUSSION

In MATLAB/Simulink, the 18-bus ship network from Fig. 1 is modeled, and a load flow analysis is performed in simulation. In this network, there are eight similar branches with numerous single-phase loads, and the generation is closely aligned with demand.

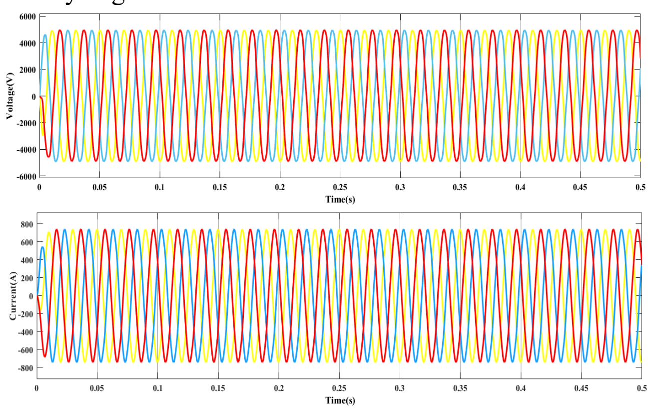

Fig. 6 – Voltage and current output of generator bus.

Based on the voltage, current and power required for the ship network, solar panels are designed. The results obtained are verified with load flow solutions obtained from the Newton-Raphson method. The maximum current that flows in the circuit is around 500A. Tie line current is around 35A. The Power rating of each generator is 3.3 MVA. The results obtained are verified by performing power flow analysis for the ship electrical network using the Newton-Raphson load flow method in MATLAB. Voltage at each bus of the ship electrical network is tabulated and the maximum per unit voltage obtained is 1.02. Since there are four similar branches, voltage at those buses is similar. Thus, the load management helps in designing the PV Source also satisfying the load demand. The RMS voltage at each bus of ship electrical network is tabulated in Table 4. Current flow at each branch is depicted in Fig. 5. Voltage and Current waveform of Generator Bus 1 is represented in Fig. 6.

Table 4

Voltage profile of the ship network.

Bus	V rms (V)	Per Unit Values
1	4776	1.02
2	4772	1.02
3	4762	1.02
4	4760	1.02
5	4708	1.01
6	4689	1.00
7	4651	0.99
8	4497	0.963
9	4487	0.961
10	4670	1.00
11	4515	0.97
12	4506	0.97
13	4607	0.99
14	4448	0.95
15	4435	0.95
16	4620	0.99
17	4455	0.95
18	4442	0.95

7. CONCLUSIONS

In the present work, load flow analysis of an 18-bus radial ship electrical network is done using MATLAB/Simulink, and the total demand of the ship network is calculated and verified using the Newton-Raphson method. Based on the load demand, solar panels are designed. The potential for the growth of green energy sources in the marine industry is significant, particularly in light of the declining availability of fossil fuels. The advancement of photovoltaic energy is an unavoidable trajectory in today's energy landscape. As a result, our effort encourages the utilisation of PV solar energy to power all the electrical loads of ships, ultimately leading to an increase in the network's efficiency and reliability.

This work aims to provide a clean and environmentally friendly source of energy for transportation in waterways. One of the significant constraints experienced by ship power engineers is the issue of affordability and accessibility. At certain times, solar energy becomes inaccessible due to the necessary time. Additionally, it is influenced by the ship's position and climatic conditions, necessitating control. For its benefits in fuel economy, ship operators use degraded oil. These pollutants are hazardous, depleting the ozone layer and leading to numerous detrimental effects on the ecosystem.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Edel Quinn Julin M: concept and methodology, analysis of data, writing original draft.
Vijayalakshmi Subramanian: concept, analysis of data, writing original draft, writing – review and editing.

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REFERENCES

1. N. Rojjana, W. Rattanawong, V. Vongmanee, Integration of Maritime Management Systems to Reduce CO2 Emissions in Sustainability, 27th International Computer Science and Engineering Conference, ICSEC, pp. 457–460 (2023).
2. J.J. Corbett, Updated emissions from ocean shipping, J Geophys Res, 108 (2003).
3. S.H. Hong, D.M. Kim, S.J. Kim, Power control strategy optimization to improve energy efficiency of the hybrid electric propulsion ship, IEEE Access, 12, pp. 22534–22545 (2024).
4. S. Wen, T. Zhao, Y. Tang, Y. Xu, M. Zhu, Y. Huang, A joint photovoltaic-dependent navigation routing and energy storage system sizing scheme for more efficient all-electric ships, IEEE Transactions on Transportation Electrification, 6, pp. 1279–1289 (2020).
5. A.T. Adel Yahiaoui, An efficient study of Pv – Wind - Battery – Electrolyzer - H2 – Tank - Fc for a remote area electrification, Rev. Roum. Sci. Techn. – Série Électrotechn. et Énerg. (2024).
6. C. Guo, Y. Sun, C. Yuan, X. Yan, Y. Wang, Q. Jiang, *Research on power load flow calculation for photovoltaic-ship power system based on PSAT*, International Conference on Renewable Energy Research and Applications, ICRERA, pp. 443–448 (2015).
7. M. Gaber, S.H. El-Banna, M.S. Hamad, M. Eldabah, *Performance enhancement of ship hybrid power system using photovoltaic arrays*, IEEE PES/IAS Power Africa (2020).
8. N. Zohrabi, J. Shi, S. Abdelwahed, *An overview of design specifications and requirements for the MVDC shipboard power system*, International Journal of Electrical Power and Energy Systems, **104**, pp. 680–693 (2019).
9. N. Djagarov, D. Tsvetanov, Z. Grozdev, J. Djagarova, *Mathematical model of a ship power system with DC power distribution system*, IEEE International Conference on Environment and Electrical Engineering, IEEE Industrial and Commercial Power Systems Europe, EEEIC / I and CPS Europe, pp. 1–8 (2022).
10. C. Park, B. Jeong, P. Zhou, H. Jang, S. Kim, H. Jeon, D. Nam, A. Rashedi, *Live-Life cycle assessment of the electric propulsion ship using solar PV*, Appl Energy, **309** (2022).
11. G.S. Spagnolo, D. Papalillo, A. Martocchia, G. Makary, *Solar-Electric Boat*, J Transp Technol, **2**, pp. 144–149 (2012).
12. S.M. Lutful Kabir, I. Alam, M. Rezwan Khan, M.S. Hossain, K.S. Rahman, N. Amin, S*olar powered ferry boat for the rural area of Bangladesh*, International Conference on Advances in Electrical, Electronic and Systems Engineering, ICAEES, pp. 38–42 (2016).
13. E. Nivolianiti, Y.L. Karnavas, J.F. Charpentier, *Energy management of shipboard microgrids integrating energy storage systems: A review*, Renewable and Sustainable Energy Reviews, **189**, pp. 114012 (2024).
14. T.L. Baldwin, S.A. Lewis, *Distribution load flow methods for shipboard power systems*, IEEE Trans Ind Appl, **40**, pp. 1183–1190 (2004).
15. K. L. Butler, N.D.R. Sarma, V.R. Prasad, *Network reconfiguration for service restoration in shipboard power distribution systems*, Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference, **2,** pp. 870 (2002).
16. H. Mohamad, Z. Zakaria, M.Z. Bin Mazlan, *Development of GUI power system load flow analysis tool based on Newton Newton-Raphson method,* IEEE 7th International Conference on Engineering Education, ICEED, pp. 29–34 (2016).
17. S. Chatterjee, S. Mandal, *A novel comparison of Gauss-Seidel and Newton-Raphson methods for load flow analysis*, International Conference on Power and Embedded Drive Control, ICPEDC, pp. 1–7 (2017).
18. A. Nur, A. Kaygusuz, *Load Flow Analysis With Newton–Raphson and Gauss–Seidel Methods in a Hybrid AC/DC System*, IEEE Canadian Journal of Electrical and Computer Engineering, **44**, pp. 529–536 (2021).
19. Ç. Karatuğ, Y. Durmuşoğlu, *Design of a solar photovoltaic system for a Ro-Ro ship and estimation of performance analysis: A case study*, Solar Energy, *207*, pp. 1259–1268 (2020).
20. A. Nur, A. Kaygusuz, *Load flow analysis with Newton–Raphson and Gauss–Seidel methods in a hybrid AC/DC system,* IEEE Canadian Journal of Electrical and Computer Engineering, **44,** pp. 529–536 (2021).
21. C.H. Han, *Strategies to reduce air pollution in shipping industry*, Asian Journal of Shipping and Logistics, **26**, pp. 7–29 (2010).
22. A.W. Hussein, M.W. Ahmed, *Solar Energy : Solution To Fuel Dilemma*, pp. 99–108 (2014).
23. I. Kobougias, E. Tatakis, J. Prousalidis*, PV systems installed in marine vessels: Technologies and specifications*, Advances in Power Electronics (2013).
24. Y. Zhang, C. Yuan, *Research on the synergy of solar-sail ship with route optimization*, ICTIS 3rd International Conference on Transportation Information and Safety, Proceedings, pp. 447–450 (2015).

25. A. Kurniawan, *A review of solar-powered boat development,* IPTEK The Journal for Technology and Science, **27** (2016).
26. Y. Oubbati, B. Khalil Oubbati, A. Rabhi, S. Arif, *Experimental analysis of hybrid energy storage system based on nonlinear control strategy*, Rev. Roum. Sci. Techn. – Série Électrotechn. et Énerg. (2023).
27. M.G. Villalva, J.R. Gazoli, E. Ruppert Filho, *Modeling and circuit-based simulation of photovoltaic arrays*, 2009 Brazilian Power Electronics Conference, COBEP2009, pp. 1244–1254 (2009).
28. Q. Shen, B. Ramachandran, S.K. Srivastava, M. Andrus, D.A. Cartes, *Power and energy management in integrated power system*, IEEE Electric Ship Technologies Symposium, ESTS, pp. 414–419 (2011).