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Perspective

Feeder Losses Analysis of Marine Vessel Power Systems: A Case Study of Container Ship Power Loss Analysis Using Newton–Raphson Method

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Abstract: Load survey has become a routine project for shipbuilding and shipping companies to investigate electrical load characteristics to enhance the power system planning and operation of marine vessels. In this brief perspective, we will outline a few steps to feeder losses analysis based on the result conducted by the load survey. The power flow and feeder loss analysis are extracted and used to determine the critical parameters that can significantly affect the system feeder losses used in the electrical load analysis in new ships. Exploring this new research direction will provide a more thorough understanding of feeder losses in marine vessel power systems. In this paper, a case study of container ship power loss analysis using the Newton–Raphson method is presented. The analysis results can provide shipbuilding corporations and ship owners with useful information for planning, designing, operating, and controlling shipboard power systems. As an energy-saving measure for ship microgrids, the frequency converters are widely used by shipyards for seawater and freshwater cooling systems and heating, ventilation, and air conditioning (HVAC) systems, so that these systems can adjust the speed of the motor according to the actual demand of the load, so as to avoid full-load operation during the motor operation. With the proposed method, other measures, such as battery energy storage systems and energy-saving lighting equipment based on LEDs, are also utilized for shipboard power demand management.

Keywords: energy efficiency; feeder losses; marine vessel power system

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1. Introduction

The impact of the shipping industry on the global climate, CO_2, Nox, Sox, and greenhouse gas emissions account for about 6%, 30%, 20%, and 1.75% of the global total emissions, respectively [1,2]. Since the signing of the Kyoto Protocol, all member states and the International Maritime Organization (IMO) are willing to cooperate with the world to reduce carbon emissions and start energy-saving plans [3]. Moreover, the Marine Environment Protection Committee (MEPC) 76 [4] member meetings held by the IMO in June 2021 demonstrated readiness. Ships must comply with the Energy Efficiency Existing Ship Index (EEXI) energy efficiency standards, effective from 1 November 2022 [5,6]. Based on the long-range goals of the Paris Climate Agreement, the EEXI will require ready-made ships to submit supporting calculations of energy efficiency, similar to the requirements of the Energy Efficiency Design Index (EEDI) Phase 2 or Phase 3 (depending on the ship type), regardless of the type of ship. All ships should undergo EEXI verification and be renewed with an International Energy Efficiency Certificate (IEEC) before the first International Air Pollution Prevention certificate (IAPP) statutory survey after 1 January 2023 [7,8]. In order to effectively master the ship power system load characteristics, dockyard companies and ship owners have discussed the electrical energy consumption patterns of different types of load clusters in the system, such as motor power equipment, lighting equipment, electronic navigation instruments and equipment, process control equipment, etc. [9–11] Numerous different types of ships (e.g., merchant ships), such as container ships, bulk carriers, liquefied gas carriers, etc., have significantly different power consumption characteristics, and the related power consumption varies with the line, operating conditions, tonnage, and equipment service time [12,13]. In order to effectively implement system planning, power supply design development, load management, and power dispatching, carriers and dockyards must learn about the power consumption characteristics of different load types, the load power consumption pattern demands, and the development of different ship types through proper system analysis, in order to plan more efficient power supply design development and make various load management strategies [14–16].

The ship power system feeder loss is mainly power distribution system loss; thus, it is of great importance to ship power capacity design and system operation management [17,18]. A shipboard power distribution system has numerous feeders, and the basic data of each feeder, such as distribution transformer capacity, conductor distribution, and location, shall be effectively mastered, which is difficult to be mastered due to the actual environment limits onboard. Therefore, it is necessary to analyze the total system line loss, where the total number of distribution transformers of different capacities is calculated; the iron loss value and copper loss value of a single transformer are provided by the equipment manufacturer and technical manual, the capacity factor of the distribution transformer is determined by the total delivery of the power distribution system, and the distribution transformer loss value of the total system is calculated.

Many methods for analyzing line loss have been proposed; however, these methods still have problems in result accuracy, as load patterns are different during different time intervals, even if in the same time interval, the randomness of load operation may result in analysis errors [19]. The first type of the power distribution system loss estimation method is power flow calculation [20,21]; the second type of network loss estimation is artificial neural networks (ANNs) [22,23]; and the third type is heuristic methods for estimating loss [24,25]. However, the above methods require high processing and enough datasets to provide precise analysis. Furthermore, these references emphasize land power system analysis; however, there are few studies regarding maritime power grids.

In this perspective article, the architectures of different types of feeders in marine vessel power systems are built, including the lengths of trunk streams and shunts, where the average delivery of different types of feeders is estimated by the total delivery of the power distribution system to analyze power flow, and line loss values in the different operating conditions of a current voyage can be deduced. After the aforesaid analysis of power distribution system loss, the proportion of the overall ship power system line loss can be calculated. This system loss estimation model can improve the unreasonable traditional method, as it uses the fixed line loss rate to estimate system loss, thus enhancing the accuracy of line loss analysis used by dockyards for new ship design, and carriers can effectively master the power distribution system loss, in order to make appropriate system operation scheduling strategies for marine vessel power systems. The main contribution of this paper can be summarized as follows:

- Introducing a new analysis strategy for ship power system loss.
- Analysis results can support shipbuilding corporations and ship owners by providing useful information for planning, designing, operating, and controlling shipboard power systems.
- Regarding the energy-saving of ship microgrids, the shipyard can use the analysis data to frequency converters for seawater and freshwater cooling systems and heating, ventilation, and air conditioning (HVAC) systems, so that these systems can adjust the speed of the motor according to the actual demand of the load, so as to avoid full-load operation during the motor operation.

- With the proposed method, other measures, such as battery energy storage systems and energy-saving lighting equipment based on LEDs, are also utilized for shipboard power demand management.

2. Ship Power Feeder Loss Analysis

In future development planning and designing of power systems, as well as making the optimum operational decisions for existing systems, power flow is very important. The main information derived from power flow operation includes the voltage magnitudes and phase angles of various buses, as well as the active power and reactive power flowing through each transmission line. The system buses must be classified into Reference Bus, PV Bus, and PQ Bus before calculation, and then, the system transmission line and tap transformer admittance matrix are built and computed by the power flow analysis method. In the power flow problem, the active power and voltage magnitude of the PV Bus are given, and if the problem is represented in polar form, the complex power of Bus i can be expressed as [26]

$$P_i = \sum_{j=1}^{n} |V_i||V_j|\left[G_{ij}cos\left(\delta_i - \delta_j\right) + B_{ij}sin\left(\delta_i - \delta_j\right)\right] \tag{1}$$

$$Q_i = \sum_{j=1}^{n} |V_i||V_j|\left[B_{ij}cos\left(\delta_i - \delta_j\right) - G_{ij}sin\left(\delta_i - \delta_j\right)\right] \tag{2}$$

where P_i and Q_i are the input active power and reactive power of Bus I, respectively; $\mid V_i \mid$ and $\mid V_j \mid$ are the voltage magnitudes of buses i and j, respectively; G_{ij} and B_{ij} are no. ij element value in the system admittance matrix Y_{bus}; δ_i and δ_j are the voltage phase angles of buses i and j, respectively; n is the number of system buses.

Based on the aforesaid nonlinear equation of power flow, the voltage magnitudes and phase angles of various system buses can be computed using the recursive numerical analysis method, and the line flow between system buses can be calculated by the following equations from the obtained results.

$$P_{ij} = \left[|V_i|^2 G_{ij} - |V_i||V_j|\left(G_{ij}cos\left(\delta_i - \delta_j\right) + B_{ij}sin\left(\delta_i - \delta_j\right)\right)\right] \tag{3}$$

$$Q_{ij} = \left[-|V_i|^2 B_{ij} - |V_i||V_j|\left(G_{ij}sin\left(\delta_i - \delta_j\right) - B_{ij}cos\left(\delta_i - \delta_j\right)\right)\right] \tag{4}$$

where P_{ij} and Q_{ij} are the active power and reactive power of line flow between buses i and j, respectively.

In terms of the ship power feeder loss analysis process used in this paper, the ship power system one-line diagram data are compiled, and the generator, power cable, transformer, and load data are collected,. Then, the data are imported into the flow analysis program. The Newton–Raphson Method is used for computation, and the flow analysis result is favorable, including the system bus voltage magnitude, line flow power, line voltage drop, and line loss. The analysis results can be used to compare the line current specifications and transformer-rated capacity in order to determine the line and transformer loads, bus voltage distribution, and line voltage drop, whether the system is overloaded or has low voltage or high voltage, and to plan or study the appropriate improvement proposals, in order to guarantee system operation safety and power quality. In addition, the main position and equipment where power distribution system loss occurs can be known according to the line loss analysis result. Then, the improvement proposal is planned, in order to guarantee system operating efficiency. The steps of the proposed analysis strategy are summarized in the computational procedure shown in Figure 1.

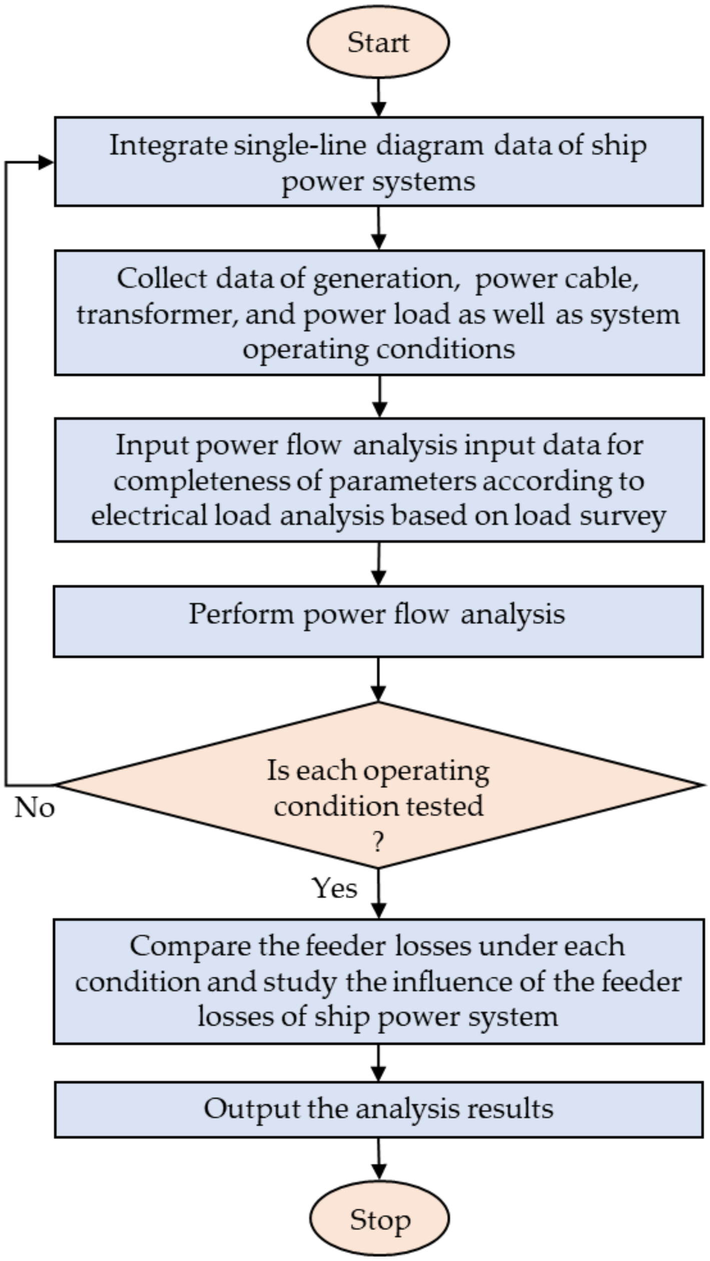

Figure 1. The computational procedure of the proposed method.

3. Case Study: Actual Container Ship Made by CSBC Kaohsiung Yard

At present, the world's shipbuilding market has formed a trend of the simultaneous development of various types of ships, such as oil tankers, bulk carriers, container ships, special ships, and offshore engineering equipment ships, accounting for 12.02%, 18.88%, 41.42%, and 1.50%, respectively. Compared with the shipbuilding market in 2020, oil tankers declined by 5.08%, bulk ships increased by 49.15%, container ships increased by 338.64%, and offshore engineering remained flat. Due to the impact of the COVID-19 epidemic in 2021, coupled with the shortage of containers in globally congested ports, the demand for shipping and container ships will increase greatly. As can be seen from Figure 2, the contracted volume of container ships in 2021 will reach 4.1 million twenty-foot equivalent units (mTEU), which is not only three times higher than that in 2020, but also the highest point since 2006 [27]. Therefore, container ships are selected for loss analysis.

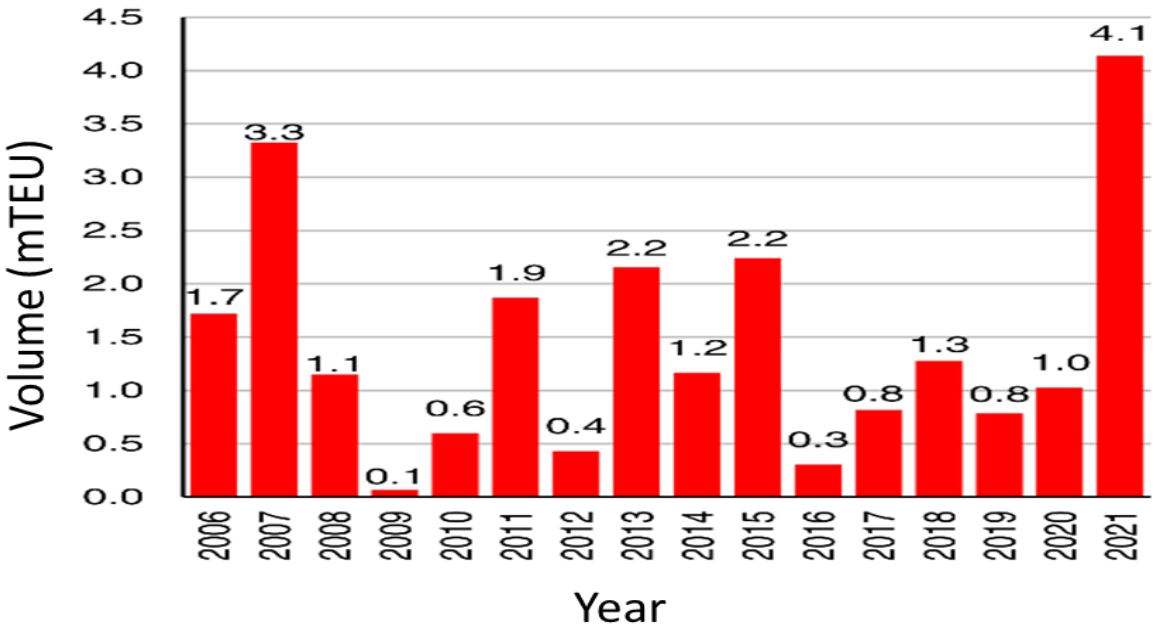

Figure 2. Container ship contracting volume variation referring to Container Intelligence Monthly [27].

The test data in this paper are derived from a container ship, which is designed as a ship with double bottom. The whole ship has 10 cargo holds, where Holds 1 to 8 are designed for dangerous goods. The ship length is 368 m, the beam is 51 m, the molded depth is 29.85 m, the loaded draft is 16.026 m, the deadweight tonnage is 146,073 tons, and the ship can load 14,198 20 ft standard containers. The new ship has excellent performance with low fuel consumption and low vibration, which meets international environmental protection and energy conservation standards. Figure 3 shows the aerial view of the actual ship studied. The main engine is MAN B&W 11S90-C10.2; MCR 50,760 kW $\times$ 78 rpm, NCR 43,146 kW $\times$ 73.9 rpm, made by Korea HYUNDAI; Hyundai Motor Company Headquarter · 12, Heolleung-ro, Seocho-gu, Seoul, Korea. For the four 6600 VAC diesel generators, the capacities are 3700 kW $\times$ 2 sets and 2800 kW $\times$ 2 sets, made by STX B&W, models 6L32/40 and 8L32/40, 720 rpm. This ship is provided with over 800 reefer container sockets; thus, the electricity requirement exceeds 10 MW, and the power grid uses medium voltage 6.6 kV. Namely, the generator output rated voltage is 6.6 KV, the high voltage side uses a dual bus, which is connected by a vacuum breaker (VCB) which is redundant for important equipment. Table 1 records the proposed ship characteristics data. Figure 4 shows the reduced power one-line diagram of the actual ship studied. The generator and major load operating conditions are shown in Table 2, while the major parameters of the transformers in the system are shown in Table 3.

Table 2 lists the At Sea, Departure, and In-Port conditions of the equipment. Departure requires operating four generators, while At Sea and In Port only run three generators. The bow thrusters work during Departure, the blower running period is identical to the bow, the Topping air compressor supplies air pressure for control, the air compressor runs during Departure, four steering gears run during Departure, and only two sets are required during At Sea. The lubricating oil pump lubricates the main engine, and the main engine runs during At Sea and Departure; thus, the lubricating oil pump also works during At Sea and Departure. As they are limited due to text length, a part of the test results are presented below, while the detailed test results can be found in [27].

Table 1. The proposed ship characteristics data.

Ship Characteristics	
Ship type	Container ship
Number of cargo holds	10 holds
Ship length	368 m
Beam length	51 m
Molded depth	29.85 m
Loaded draft	16.026 m
Deadweight tonnage	146,073 tons
Main engine	MAN B&W 11S90-C10.2; MCR 50,760 kW × 78 rpm, NCR; 43,146 kW × 73.9 rpm; made by Korea HYUNDAI
Diesel generators	Four 6600 VAC diesel generators, the capacities are 3700 kW × 2 sets and 2800 kW × 2 sets, made by STX B&W, models 6L32/40 and 8L32/40, 720 rpm.
Container sockets	800 reefer; 10 MW
Output-rated voltage	6.6 KV
Circuit breaker type	Vacuum circuit breaker

Figure 3. The aerial view of the study ship.

Table 2. Operating conditions of generators and major loads.

Operating Condition / Generator and Load Power	At Sea	Departure	In Port
Generators 3700 kW(G1,4);2800 kW(G2,3)	G1,2,3 on	G1,2,3,4 on	G1,2,3 on
Bow Thrusters (1800 kW × 2)	off	No.1,2 on	off
L.O. Pumps (250 kW × 1)	No.1 on	No.1 on	off
Aux. Blower (132 kW × 2)	off	No.1,2 on	off
Air Compressor (86 kW × 2)	off	No.1,2 on	off
Steering Gears (110 kW × 4)	No.1,2 on	No.1,2,3,4 on	off

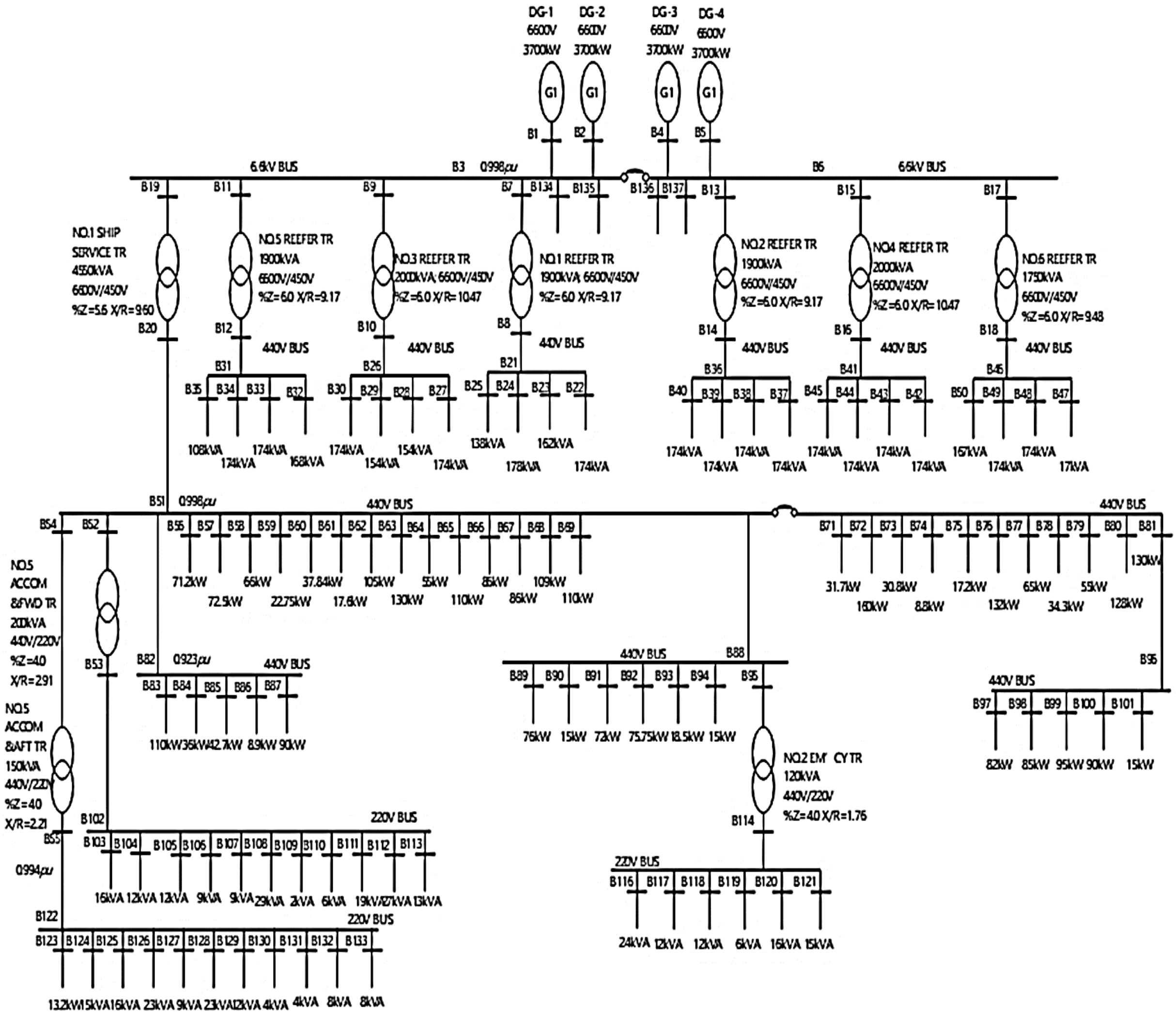

Figure 4. A simplified one-line diagram of the practical ship power system.

Table 3. Transformer equipment parameters.

Transformers	Voltage (V)	Capacity (kVA)	Impedance		Connection
			Z(%)	X/R	
SHIP SERVICE TR	6600/440	4550	5.5	9.6	Delta-Delta
NO.1 REEFER TR	6600/440	1900	6	9.17	Delta-Delta
NO.2 REEFER TR	6600/440	2000	6	9.17	Delta-Delta
NO.3 REEFER TR	6600/440	1750	6	10.47	Delta-Delta
NO.4 REEFER TR	6600/440	1900	6	10.47	Delta-Delta
NO.5 REEFER TR	6600/440	2000	6	9.48	Delta-Delta
NO.6 REEFER TR	6600/440	1750	6	9.48	Delta-Delta
ACCOM&FWD TR	440/220	200	4	2.91	Delta-Delta
E/R&AFT TR	440/220	150	4	2.21	Delta-Delta
EM’CY TR	440/220	120	4	1.76	Delta-Delta

The test results of voltage distribution over various buses in the Departure operating conditions are shown in Figure 4. It is observed in Figure 4 that, as the ship electric network architecture is a radial power system, the bus closer to the power supply has a higher voltage, and the bus closer to the feeder terminal has a lower voltage. The voltage difference between the buses in the system in different operating conditions is due to the different load capacities of various buses, leading to different line flows; thus, the system bus voltages are different. The bus voltage is lower in the Departure operating condition. In addition, during the At Sea, Departure, and In Port operating conditions, the line voltage drop changes drastically in the ship service transformer. In the three operating conditions, the large line voltage drop occurs in Bus “B96” and the tail end of the 440 V bus, as there is no transformer tapping for adjustment.

The reefer container sockets are stepped down to 440 V by six transformers, as the power is supplied under medium voltage; thus, the voltage per unit values are higher than 0.98 p.u. in the flow analysis. As the rated voltage of auxiliary engine equipment and control equipment is 440 V, the required power must be supplied from the high-tension side bus by the ship service transformer, while the 220 V power for living equipment and accommodation is supplied from the low-tension transformers in the engine room. As the low-tension transformer is located near the end-use equipment, the low-voltage equipment is connected to the end of the electric network, where the total length from the power supply to the endmost bus cable is about 274 m, and the bus voltage is 0.88 p.u.~0.91 p.u. The bus voltages in different operating conditions are lower than the legally specified 0.15 p.u. If the analysis result is not accepted, the line voltage drop can be reduced by regulating the transformer tapping, thickening the cable, or improving the power factor, in order to maintain the system power quality.

In practice, the ship power management system (PMS) sets the generator parallel connection condition when the single unit load exceeds 90%, and sets the demand factor of the reefer container sockets as 0.6 in the load analysis design. Therefore, in the Departure operating condition, the flow power of the NO.1~NO.6 reefer transformers is 617~670 kVA, the flow power in the operation of the ship service transformer is 4676 kVA, which is 103% of the rated value, the quarter transformer flow power is 120 kVA, the load factor is 80%, the engine room transformer flow power is 132 kVA, the load factor is about 66%, the transformer flow power for emergency power supply is 68 kVA, and the load factor is about 57%. The high-tension transformer flow power during At Sea and In Port operating conditions is 617~670 kVA; however, the ship service transformer flow power is 3678 kVA in the At Sea operating condition, and 3505 kVA during the In-Port operating condition, while the other power flow through the transformers is similar to the Departure operating condition. The test results show that the large line flow occurs in the ship service transformer during At Sea, Departure, and In Port operating conditions, which is a system operation weakness. The current through the transformer is 4736 A in the At Sea operating condition, 6014 A in the Departure operating condition, and 4503 A in the In-Port operating condition. It is observed that the current through the ship service transformer in various operating conditions has not exceeded the rated current of 6256 A of the cable connected to the transformer. In high load operating conditions (Departure), the ship service transformer may be overloaded, as the probability of the simultaneous operation of engine room equipment is very low, and the time is very short; thus, such transformer overloading will not heavily influence the system supply reliability. If transformer overloading is unacceptable, appropriate system scheduling control or a load management strategy can be made or planned to enhance the system operation safety. In addition, the test results show that the result of power flow analysis can provide the overall system performance and possible operation weakness, in comparison to the traditional empiric single-point or single equipment-based ship power system design mode, as it can provide engineers more information for system operation planning.

Table 4 shows the power feeder losses in different operating conditions, and the top 50 feeders with heavy losses in various operating conditions are selected and compared. According to Tables 4 and 5, the total feeder loss in At Sea, Departure, and In Port operating conditions, including power cable loss and transformer loss, is 272.1 kW, 419.6 kW, and

250.3 kW, respectively, and the total load is 7496 kW, 11965 kW, and 7074 kW, respectively. The percentages of total feeder loss and total load of the three operations are 3.6%, 3.5%, and 3.54%, respectively. According to the test results, due to the low voltage of 440 V, long bus lines, and high current, the low voltage feeder loss is relatively high. The current through the load end of the ship service transformer is 6041 A in the Departure operating condition, and the loss is 269 kW, accounting for 64% of the total loss of 419.6 kW. The test results show that, in the three operating conditions, the maximum feeder loss occurs in the feeder of this 440 V transformer load end, and the loss value is several times higher than the high-tension transformer. Power flow analysis can provide and reflect the total system loss distribution over the actual maritime power network, which will help engineers in planning, designing, and managing ship power systems.

Table 4. The power feeder losses under different operating conditions.

From Bus	To Bus	Losses (kW)		
		At Sea	Departure	In Port
Bus20	Bus51	166.9	269.1	150.8
Bus19	Bus20	17.1	27.5	15.4
Bus51	Bus96	12.6	17.3	12.5
Bus51	Bus76	3.2	13.9	4.6
Bus51	Bus88	2.8	4.9	3.1
Bus88	Bus89	2.7	3.4	2.8
Bus51	Bus81	2.5	3.3	2.6
Bus51	Bus68	2.2	3.2	2.5
Bus54	Bus55	2.1	3.1	2.2
Bus51	Bus54	1.9	3.0	2.1
Bus51	Bus80	1.9	2.8	2.0
Bus51	Bus62	1.8	2.6	1.9
Bus17	Bus18	1.7	2.3	1.8
Bus96	Bus99	1.6	2.0	1.7
Bus5	Bus6	1.5	2.0	1.6
Bus52	Bus53	1.5	1.9	1.5
Bus96	Bus98	1.5	1.9	1.5
Bus11	Bus12	1.4	1.8	1.5
Bus13	Bus14	1.4	1.7	1.4
Bus46	Bus50	1.4	1.7	1.4
Bus51	Bus52	1.4	1.6	1.4
Bus7	Bus8	1.4	1.5	1.4
Bus88	Bus91	1.4	1.5	1.4
Bus15	Bus16	1.3	1.4	1.3
Bus9	Bus10	1.3	1.4	1.3
Bus95	Bus114	1.1	1.4	1.1
Bus10	Bus26	1.0	1.4	1.0
Bus4	Bus6	1.0	1.4	1.0

Table 4. *Cont.*

From Bus	To Bus	Losses (kW)		
		At Sea	Departure	In Port
Bus51	Bus63	1.0	1.4	1.0
Bus51	Bus64	1.0	1.3	0.8
Bus51	Bus79	0.9	1.3	0.8
Bus51	Bus57	0.8	1.1	0.7
Bus55	Bus122	0.8	1.0	0.7
Bus51	Bus56	0.7	1.0	0.6
Bus102	Bus103	0.6	1.0	0.6
Bus2	Bus3	0.6	1.0	0.6
Bus3	Bus19	0.6	1.0	0.6
Bus41	Bus42	0.6	1.0	0.6
Bus53	Bus102	0.6	1.0	0.5
Bus82	Bus87	0.6	1.0	0.5
Bus1	Bus3	0.5	0.9	0.5
Bus21	Bus24	0.5	0.9	0.5
Bus21	Bus25	0.5	0.8	0.5
Bus36	Bus39	0.5	0.8	0.5
Bus36	Bus40	0.5	0.7	0.5
Bus51	Bus58	0.5	0.7	0.5
Bus51	Bus77	0.5	0.6	0.4
Bus82	Bus83	0.5	0.6	0.4
Bus96	Bus100	0.5	0.6	0.4
Bus96	Bus101	0.5	0.5	0.4

Table 5. The extracted results of the ship power losses at different states.

Operating Condition / Extracted Results	At Sea	Departure	In Port
Total feeder loss (kW)	272.1	419.6	250.3
Total load (kW)	7496	11,965	7074
The percentages of total feeder loss and total load (%)	3.60	3.50	3.54
Effective line length (m)	15,939	16,195	15,843
Effective line average diameter (mm^2)	29.5	30.7	28.96
Total transformer capacity (kVA)	16,320	16,320	16,320
Actual load ratio of the transformer (%)	48.4	54.5	47.9

In terms of the actual ship power system data for testing in this paper, the top 50 cable conductors with heavy losses in various operating conditions are selected and compared with the test results of power feeder losses under different operating conditions. According to the test results, the total feeder line loss during At Sea, Departure, and In Port operating conditions, including power cable loss and transformer loss, is 272.1 kW, 419.6 kW, and 250.3 kW, respectively, and the total load is 7496 kW, 11965 kW, and 7074 kW, respectively. The percentages of the total feeder loss and total load of the three operations are 3.6%, 3.5%, and 3.54%, respectively.

4. Conclusions and Future Outlook

This paper introduces an effective analytic method for power loss in ship power systems. A case study of container ship power loss analysis using the Newton–Raphson method is presented. The proposed method can provide the loss analysis without the need for high processing or high computational burden, as well as no need for training datasets compared with the previous methods in the literature. Furthermore, the loss analysis of the ship microgrid has not yet been discussed; the power flow and feeder loss analysis results are extracted and used to determine the critical parameters that can significantly affect the system feeder losses used in the electrical load analysis in new ships. In this paper, various operating conditions are selected and compared with the test results of power feeder losses under different operating conditions. According to the test case used in the analysis, the total feeder line losses during At Sea, Departure, and In Port operating conditions, including power cable loss and transformer loss, are 272.1 kW, 419.6 kW, and 250.3 kW, respectively, and the total load is 7496 kW, 11965 kW, and 7074 kW, respectively. The percentages of the total feeder loss and total load of the three operations are 3.6%, 3.5%, and 3.54%, respectively. These analysis results can provide shipbuilding corporations and ship owners with useful information for planning, design, operation, and control of shipboard power systems. However, the proposed method requires enough details about the studied power system to give a precise analysis. The introduced perspective of ship power feeder loss analysis can be extended to different types of ships considering different environmental and emission effects, such as temperatures, humidity, and decarbonization in future work.

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