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Power flow analysis of DC distribution system in a ship with non-electric propulsion

Akhmad Reinaldy Kurniawan, Adi Kurniawan, Sardono Sarwito, Ahlur Roi Novanto Gumilang, Firman Budianto
Department of Marine Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia

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ABSTRACT

Direct current (DC) shipboard power distribution system offers higher power efficiency and voltage stability compared to the alternating current (AC) systems due to lower impedance. The implementation of DC distribution system in all-electric ship seems to be worthy since the reduction of power loss and voltage drop could overcome the drawback of DC system. However, the effectiveness of DC distribution system in ship with non-electric propulsion has not been investigated yet. Unlike in an all-electric ship, electric power flow in the distribution system of a ship with mechanic propulsion is considerably lower. The study aims to provide numerical analysis of power loss and voltage drop reduction on DC distribution system that applied to a ship with mechanic propulsion. The power flow analysis is performed on a tanker ship. Contrary to the hypothesis, the results show that the DC power distribution increase the power losses about 15% compared to AC system due to the addition of rectifier and inverter. However, the voltage drops are decreased in DC distribution system. Further investigation in the other aspects should be performed before concludes whether DC distribution system is worthy to be used in the aforementioned ship.

Corresponding Author:

Adi Kurniawan
Department of Marine Engineering, Institut Teknologi Sepuluh Nopember
Jl. Raya ITS, Sukolilo, Surabaya 60111, Indonesia
Email: adi.kurniawan@ne.its.ac.id

1. INTRODUCTION

For decades, alternating current (AC) distribution system has been dominantly used in marine vessels, especially in a large one [1]–[3]. In most vessels, the main electric supply is produced by 3-phase diesel generator while the electric loads are dominated by AC devices, either single or three-phase loads [4]. Moreover, efficient energy conversion from AC to direct current (DC) or vice versa had not been well-developed at that time. Therefore, the selection of AC system to distribute the electric energy from the sources to the load is reasonable and undoubtedly the best decision at that time.

Recently, compact and high-efficient power electronic converters have been developed. These inventions have solved the problem related to the lack of an efficient energy conversion process, as the rectifier and inverter may be able to convert electrical energy from AC to DC or vice versa respectively, with efficiency of up to 97% [5], [6]. The efficient energy conversion leads to the possibility to use DC shipboard distribution systems even though the sources and the dominant loads are AC devices.

DC distribution systems offer some advantages compared to the AC system [4]. One of them is the lower cable impedance due to the absence of inductive reactance caused by zero voltage frequency [7]. Cable impedance is directly proportional to the power loss due to the heat dissipation on the cable. The lower cable impedance leads to not only power loss, but also lower the voltage drop in distribution line, as the voltage drop is also directly proportional with the cable impedance.

Power loss and voltage drops are important parameters that need to be minimized in power system [8]–[11]. The reduction of power loss is directly related with the reduction of required generator output power. With lower power loss in the distribution cables, the output power of the generator to supply the same load profile can be lower compared with in the system with higher power loss. As the generators in marine vessels are mostly powered by diesel engines, the reduction of required generator output power may lead to the reduction of fuel oil consumptions of the engines. Further, the daily operation cost and the gas emission produced by the vessel can be reduced [12], [13].

The potential reduction in voltage drop is also an important objective as the excessive voltage drop may damages the equipments [14]. In AC distribution system, some methods such as the use of flexible alternating current transmission systems (FACTS) devices [9] and distributed generation system [15] has been investigated to reduce voltage drop and to increase voltage stability profile. With the reduction of voltage drop, the probability of damaged equipments may also decreased.

On land application, DC system has been frequently analyzed to be applied for high voltage DC (HVDC) transmission systems. The application of HVDC transmission system is thought to be more advantageous than the medium voltage DC (MVDC) or low voltage DC (LVDC) distribution system because HVDC transmission has considerably longer cables, resulting in higher total impedance. Thus, it is more significant to decrease the impedance by reconfigure HVAC to HVDC transmission system compared to reconfigure MVAC or LVAC to MVDC or LVDC distribution systems [16]–[19]. Greater reduction of impedance will lead to greater reduction of power loss and voltage drop which is preferable.

The same case could not be applied to shipboard electrical power system as there is no long transmission system. The longest line in the shipboard power system extends from the medium or low voltage distribution line between main switch board (MSB) to the deck's panels. Therefore, in most cases, researches of the application of DC lines on shipboard electrical power system is applied on MVDC distribution system [3], [7], [20]–[24], while in few cases are developed for LVDC distribution system [25], [26].

Even though the advantages of the shipboard DC distribution system in the aspect of power loss and voltage drop have been frequently explained theoretically, the numerical investigations to show how effective it is compared with the AC distribution system can hardly be found [27]–[29], especially, for the ships with non-electric propulsion. As most of the merchant ships in Indonesia is still using mechanical propulsion system, a study to investigate the feasibility of DC distribution system in such ships is required, including the effectiveness in power loss and voltage drop compared with conventional AC distribution system. In ships with non-electric propulsion system, the electric power flow in the distribution system is considerably lower, thus, the reduction of power loss and voltage drop by applying DC distribution system may not as significant as in the all-electric ship.

This study aims to show the effectiveness of DC distribution system on a typical ship in Indonesia which traditionally use AC distribution and mechanic propulsion system. The effectiveness is focused on the power loss and voltage drop in DC system compared with in AC distribution system without changing the electric power generations and loads. The results of this study could give a consideration for shipyard industry whether to stick with AC distribution system or to reconfigure their vessels to DC distribution system. The method applied in this study is presented in section 2 while the results and the conclusion are presented in sections 3 and 4 respectively.

2. RESEARCH METHOD

2.1. System overview

The load flow analyses are performed on both the AC and DC shipboard system. The configuration of both systems are shown in Figure 1, with Figure 1(a) represent the AC distribution system while Figure 1(b) represent the DC distribution system. Both systems are supplied by three 3-phase AC synchronous generators with capacity of 650 kW, resulting 1,950 kW of total available power. The equal loads are given to both systems. There are four load profiles that determined by the operation modes of the ship. The operation modes consist of normal sailing, loading-unloading of the cargo, standby at port, and port departure and arrival. The load profile on each operation mode is different because the required equipment to do the operation are also different. For example, the largest load, the cargo pumps, are only used during the loading-unloading of the cargo and are not operated on the other operation conditions. Other loads may also be operated only in one operation mode, or in multiple mode. Even some loads are operated in more than one ship's operation modes, some of them are operated in different load percentage in each mode. For example, the hydraulic pump for steering gear is expected to be operated at 30% during normal sailing but is expected to be operated at 50% during port departure and arrival since the later mode needs more maneuver to follow the safe path. The ship's dimension and generator specifications are listed in Table 1, while the load profiles on each operation mode are listed in Table 2.

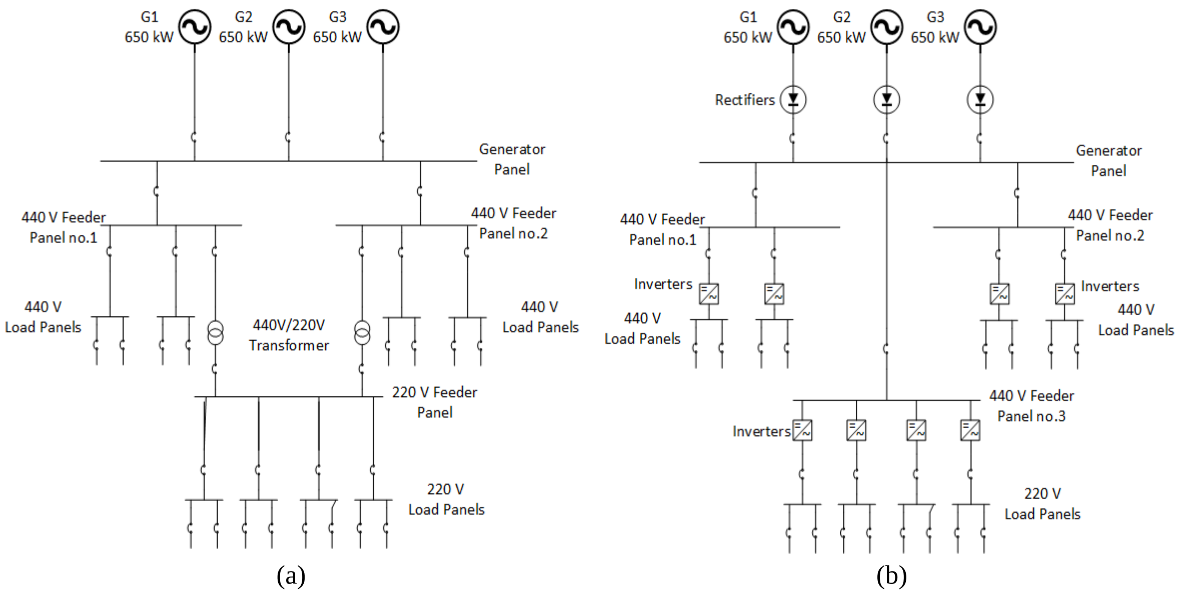

Figure 1. Simplified one-line diagram of the ship distribution system (a) AC system and (b) DC system

Table 1. Principal dimension and generator data of the sample ship

Parameter	Abbreviation	Value	Unit
Deadweight tonnage	DWT	17,500	DWT
Length between perpendiculars	L_{pp}	154	m
Beam	B	26	m
Draft	T	7	m
Number of main generators	n_g	3	Set
Generator's active power	P_g	650	kW
Generator's apparent power	S_g	813	kVA
Generator's voltage	V_g	450	V
Generator's frequency	f_g	60	Hz

Table 2. Load profiles on various ship's operation modes

Ship's Operation Mode	Number of Generator	Load Consumption (kW)	Generators Load Factor (%)
Normal sailing	1	547	84
Cargo loading-unloading	2	1046	80
Standby at port	1	273	42
Port departure and arrival	2	532	41

In this study, the difference between AC and DC systems is specified in the system design and equipments between the generators and the load panels. In AC distribution system, all of the electricities flow between generators and the loads are in AC form, except for some specific loads, in example for communication and navigation devices in the bridge deck. The electric power flows from the generators to the generator bus, then spread to two 440 V buses and a 220 V bus. The 440 V buses are connected to load buses that connected to three-phase loads including most of the pumps and engine room supply fan among others. The 220 V bus is exclusively used to conduct the power to the single-phase loads such as lightings and electric sockets through several load buses. The voltage received by the 220 V bus comes through two transformers which each connects a 440 V bus to the 220 V bus. The 220 V bus receive supply from two different 440 V buses in order to maintain the supply power, as the 220 V bus also connected with the essential navigation and communication loads through a rectifier. Because the AC loads used in this ship require 60 Hz of voltage frequency, the generators speed need to be maintained to keep the generated frequency to be constant at 60 Hz.

The reconfiguration from AC to DC distribution system conducts the removal of transformator and on the other hand, the addition of power electronic converters in the form of rectifier and inverter. The rectifiers which convert AC to DC voltage are placed after each of the generator before the powers flow to the generator bus. As a result, the generator bus needs to be converted to DC bus. The connections between generator bus and the two 440 V buses are not changes, except for the protection devices. The original lines between 440 V buses and 220 V bus are removed and the original 220 V bus is converted to the third 440 V bus, and directly connected to the generator bus. Like the generator bus, all of the 440 V buses are also converted to DC bus. The power from each 440 V bus is shared to the load buses through three-phase inverters. The inverters define the voltage required by the load buses, either 440 V or 220 V. In total, there are 10 inverters connect the 3 of 440 V bus to 37 load buses. Each inverter handles several load buses with the detail is listed in Table 3.

Table 3. Grouping of load buses

Load Bus	Load Bus Group's No.	Power (kW)
Floor no.1	Group 1	12
Vacuum Pump		18.2
No. 1 DB E/R DB Purifier	Group 2	20.2
E/R 2nd Deck No. 1		23.6
Sewage Treatment Plant		3.15
No. 2 DB E/R DB Purifier		9.57
E/R 3rd Deck No. 1		42.6
Fresh Water Hydrant		10.1
GSP 1		176.43
Incinerator		21.2
Accommodation Vent. Fan	Group 3	6.12
Upper Deck No.1		6.87
Hydrant Control Valve		3.9
Air Condition Plant		57.2
Provision Crane		14.28
Prov. Refrigeration Plant	Group 4	13
Floor No.2	Group 5	151.8
Sanitary SW		8.73
E/R 2nd Deck No. 1	Group 6	42.4
No. 2 DB E/R DB Purifier		9.16
Thermal Oil Heater		112
GSP 2		172.96
E/R 3rd Deck No. 2		44.27
DB G-1	Group 7	36.5
Upper Deck No.2		9.49
DB G-2	Group 8	8.49
E/R 3rd Deck 220 V		15.2
DB L-1		6.25
DB L-2		0.6
DB L-3		1.64
DB/ACC	Group 9	0.93
DB L-4		1.51
DB L-5		1.42
DB L-6		0.38
DB L-7		2.43
ESB 440 V	Group 10	16.18
ESB 220 V		8

The grouping of load buses that share an inverter is based on the location and also to limit the capacity of required inverter to be less than 600 kVA. The sharing of inverter between buses that far from each other is avoided, as the long cables carried AC voltage will be required, thus, increases the power loss in whole system. In the DC distribution system, the 60 Hz frequency required by the loads can be regulated by the inverters. While it is not discussed in this current research yet, the independency of frequency inflicts that the generators can be regulated at their optimum speed instead of the constant speed.

2.2. Load flow analysis

In this study, the load flow analyses are performed to observe the power loss between buses and the voltage drop on each bus, both in AC and DC distribution systems. The buses to be analyzed consist of the generator bus, three distribution buses, and 37 load buses. The total power losses can also be observed by calculate the total power generated by the generators, as the total generation power is the summation between the total power absorbed by the loads and the total power losses. The power flow analyses for both systems are performed using simulation software by defining the specification of all of the equipments, including generators, loads, buses, and also cables. The load profiles are adjusted to the ship's operation mode. The calculation is based on the Newton-Raphson method. The equation to calculate the active and reactive power generated by the generator that connected to the load buses:

$$P_g = |V_g||V_g|G_{gg} + |V_g||V_l|G_{gl}\cos(\theta_g - \theta_l) + |V_g||V_l|B_{gl}\sin(\theta_g - \theta_l) \quad (1)$$

$$Q_g = |V_g||V_l|G_{gl}\sin(\theta_g - \theta_l) - |V_g||V_g|B_{gg} - |V_g||V_l|B_{gl}\cos(\theta_g - \theta_l) \quad (2)$$

where P_g and Q_g are the active and reactive power generated by the generator, V_g and V_l are the voltage on the generator and load bus, θ_g and θ_l are the phase angle of voltage on the generator and load bus, G is the line conductance between buses, and B is the line susceptance between buses. The iteration to find the voltage and phase angle on load bus can be calculated:

$$P_l = |V_l||V_g|G_{lg}\cos(\theta_l - \theta_g) + |V_l||V_l|G_{ll} + |V_l||V_g|B_{lg}\sin(\theta_l - \theta_g) \quad (3)$$

$$Q_l = |V_l||V_g|G_{lg}\sin(\theta_l - \theta_g) + |V_l||V_g|B_{lg}\cos(\theta_l - \theta_g) - |V_l||V_l|B_{ll} \quad (4)$$

where P_l and Q_l are the active and reactive power received by the load bus.

3. RESULTS AND DISCUSSION

The results of the load flow are analyzed in the form of power loss and voltage drop according to the numerical simulation using Newton-Raphson method. The difference of total power losses between AC and DC system is only affected by the power loss in the distribution line, as the power losses in the load are equal. The power flow ensure that each load receive their required active and reactive power. Therefore, the active and reactive power generated by the generators in AC and DC system are impacted by the impedance in the distribution line that should be compensated. With the equal loads, the higher impedance in the distribution line will command higher current, thus, leads to the higher power loss and higher power compensation by the generators. Meanwhile, the power flow simulation also ensure that the output voltage of the generators is maintained to their ratings. As the current flow through the impedance of the distribution line, the voltage drop occurs and the load buses receive the lower voltage than the output voltage of the generators. Therefore, it is important to observe if the voltages received by the load buses are still meet the standard. The comparison of the total generator's power for each system in each operation mode to justify the total power losses is presented in Table 4.

Table 4. Comparisons of power generation between AC and DC distribution system

Ship's Operation Mode	P_{AC} (kW)	P_{DC} (kW)	Q_{AC} (kVAR)	Q_{DC} (kVAR)	S_{AC} (kVA)	S_{DC} (kVA)
Normal sailing	1,061	1,120	553.4	841	1,196.6	1,400.8
Cargo loading-unloading	1,205.4	1,271.7	618.3	955.2	1,354.68	1,590.42
Standby at port	520.4	549.5	291.3	412.7	596.38	687.22
Port departure and arrival	1,205.4	1,208.1	618.3	907.2	1,354.68	1,510.89

Opposite to the expectation, in the DC distribution system, the generators need to generate higher power, both on their active, reactive, and naturally apparent power. The higher power generated by the generators indicates the higher power losses in the distribution system. While the power losses in DC cable are lower, the addition of 3 large rectifiers and 10 inverters causing higher total power losses. The rectifiers and inverters modelled in the simulation are as real as possible, with 95% of efficiency. Therefore, with their large capacity, there are about 5% losses in each device, causing the higher total losses.

The observation of the bus voltages shows positive results as the voltage drops in the DC distribution system are smaller than in the AC system. However, the impact is tiny, as all of the voltage drops in the AC distribution system are already smaller than 1%. An example of voltage drop comparison for each load bus during sailing mode is shown in Table 5.

Table 5. Comparisons of voltage drop between AC and DC distribution system during sailing condition

No	Bus Group	V_{rating}	$V_{d\text{-}AC}$	$V_{d\text{-}DC}$
1	Floor No. 1	440	0.10%	0.00%
2	Vacuum Pump	440	-	-
3	No. 1 DB E/R DB Purifier (MSB 450 V No. 1)	440	0.95%	0.75%
4	E/R 2nd Deck No. 1	440	0.18%	0.03%
5	Sewage Treatment Plan	440	0.11%	0.02%
6	No. 2 DB E/R DB Workshop (MSB 450 V No. 1)	440	0.14%	0.68%
7	E/R 3rd Deck No. 1	440	0.12%	0.03%
8	Fresh Water Hyd.	440	0.75%	0.74%
9	GSP 1	440	0.11%	0.03%
10	Incinerator	440	0.16%	0.53%
11	Accommodation Vent. Fan	440	0.49%	0.31%
12	Upper Deck No. 1	440	0.11%	0.00%
13	Hyd. Control Valve	440	0.72%	0.54%
14	Air Condition Plant	440	0.35%	0.21%
15	Provision Crane	440	-	-
16	Prov. Refrigeration Plan	440	0.61%	0.00%
17	Floor No. 2	440	0.10%	0.00%
18	Sanitary SW	440	0.57%	0.31%
19	E/R 2nd Deck No. 2)	440	0.16%	0.06%
20	No. 1 DB E/R DB Purifier (MSB 450 V No. 2)	440	0.25%	0.15%
21	Thermal Oil Heater	440	0.19%	0.09%
22	GSP 2	440	0.14%	0.04%
23	E/R 3rd Deck No. 2)	440	0.13%	0.02%
24	DB G-1 (MSB 450 V No. 2)	440	0.34%	0.17%
25	Upper Deck No. 2	440	0.10%	0.00%
26	DB G-2 (MSB 220 V)	220	0.39%	0.13%
27	E/R 3rd Deck 220 V	220	0.31%	0.03%
28	DB L-1	220	0.64%	0.06%
29	DB L-2	220	0.40%	011%
30	DB L-3	220	0.64%	0.34%
31	DB/ACC (MSB 220 V)	220	0.33%	0.03%
32	DB L-4	220	0.63%	0.28%
33	DB L- 5	220	0.68%	0.20%
34	DB L- 6	220	0.41%	0.07%
35	DB L- 7	220	0.97%	0.35%
36	ESB 450 V	450	0.15%	0.00%
37	ESB 220 V	220	0.80%	0.41%

4. CONCLUSION

In this paper, load flow investigation of DC electric distribution system in ship with non-electric propulsion is presented. While the DC distribution system has lower cable impedance, the results show that the power losses in the DC distribution system is unexpectedly higher than in AC system. The origin of the higher losses in the DC distribution system is the addition of a number of rectifier and inverter used to convert electrical energy between the generators, distribution lines, and loads. The decrease in the voltage drops in DC system does not give much help as the numbers are insignificant. However, further investigation is required before eliminate DC distribution system for ship with non-electric propulsion. There are possible advantages needs to be analyzed such as the reduction of short-circuit current and the decrease of fuel oil consumption of the diesel generator due to the flexibility of the rotational speed compared with a certain fixed speed in the AC distribution system.

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BIOGRAPHIES OF AUTHORS

Akhmad Reinaldy Kurniawan received B.Eng. degree in marine engineering from Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia, in 2021. He was a member of Marine Electrical and Automation Laboratory. His bachelor thesis discussed about the power flow analysis of DC distribution system in ship with non-electrical propulsion. He can be contacted at email: reinaldyakhmad@gmail.com.

Adi Kurniawan was born in Surabaya, Indonesia in 1989. He received the B.Eng. and M.Eng. degrees in electrical engineering, power systems, from Institut Teknologi Sepuluh Nopember (ITS), Surabaya, Indonesia, in 2011 and 2013, respectively. He received Dr. Eng. in transportation and environmental systems from Hiroshima University in 2020. Currently, he is a lecturer in the Department of Marine Engineering of ITS. His research interest includes implementation of renewable energy and efficient electrical power system in marine vessel. He can be contacted at email: adi.kurniawan@ne.its.ac.id.

Sardono Sarwito was born in Solo, Indonesia in 1960. H received the B.Eng. in electrical engineering from Institut Teknologi Sepuluh Nopember (ITS) and M.Sc. in ship production from Strathclyde University, Glasgow, Scotland in 1985 and 1997 respectively. He received Ph.D degree in Marine Engineering from ITS in 2020. Currently, he is a lecturer in the Department of Marine Engineering of ITS. His research interest includes implementation of renewable energy and efficient electrical power system in marine vessel. He can be contacted at email: sarsar@its.ac.id.

Ahlur Roi Novanto Gumilang received B.Eng. degree in marine engineering from Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia, in 2021. He was a member of Marine Electrical and Automation Laboratory. His bachelor thesis discussed about the short-circuit analysis of DC distribution system in ship with non-electrical propulsion. He can be contacted at email: ahluroigumilang@gmail.com.

Firman Budianto received B.Eng. degree in marine engineering from Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia, in 2021. He was a member of Marine Electrical and Automation Laboratory. His bachelor thesis discussed about the harmonic analysis of DC distribution system in ship with non-electrical propulsion. He can be contacted at email: fbudianto210799@gmail.com.