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Short-circuit current analysis of DC distribution system in a ship with non-electric propulsion

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ABSTRACT

Converting conventional AC radial shipboard distribution system to DC system has been recognized as a potential high impact solution to reduce ship's fuel consumption. As big ships in Indonesia commonly use low voltage AC (LVAC) distribution system an effort to apply low voltage direct current (LVDC) distribution system without replace the propulsion system is a plausible choice. However, technical and economical investigations are required before recommendation to convert the shipboard distribution system to LVDC is officially launched. In this study, technical aspect in the term of short-circuit current is discussed. The goal of this study is to analyze how much the impact on the short-circuit current when LVDC system replaces LVAC system. The impact may affect the feasibility of LVDC system as the short-circuit current in a system dictate the scheme and capacity of the protection devices. Numerical simulations on a sample vessel are performed to obtain the profile of maximum short-circuit currents on all panels. The results show that the utilization of LVDC system decreases the short-circuit current by 10 times. Further investigations on the economic aspect needs to be performed to give clearer view of the feasibility of the LVDC system.

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1. INTRODUCTION

Marine vessels are essential transportation modes, especially for transporting logistics from one port to another. They are the executor of maritime transport which contribute to more than 70% of global trade both in volume and value [1]. Although air freight logistic is developing in recent years, the domination of marine transportation is unlikely to be taken soon.

As one of the major transportation modes, marine vessels used a fair share of energy consumption. In 2011, marine transportation took 6.3% of global oil consumption and contributed to 3.36% of global CO_2 emission [2]. Although the emission of marine vessels is not as much as the contribution from industry and road transportation, efforts to decrease ships energy consumption are worth doing as the number of vessels is predicted to be continuously increased. International Maritime Organization (IMO) also targeting the ship emissions to be reduced in half by 2050 [3].

Possible methods to decrease ship energy consumption in the electrical power system including the engagement of renewable energy resources [4]–[7], optimal power management system [8], [9], and efficient distribution systems [10], [11]. In Indonesia, most of vessels are still using diesel engines in their propulsion system and conventional radial AC distribution systems in their electrical grid [12]. Therefore, one of the most reasonable choices as the first step to decrease energy consumption for ships operated in Indonesia is to improve the efficiency of power distribution system.

There are 2 possible choices to improve the efficiency of the shipboard power distribution system. First, to change the distribution system to AC zonal system. Compared to AC radial distribution system, AC zonal system not only has better efficiency, but also power continuity. However, AC zonal system has a higher voltage drop than conventional radial distribution system [13].

The second solution is to change to the DC distribution system. The DC distribution system offers even higher power efficiency and voltage stability compared to AC zonal system [14]. The nature of zero frequency in DC power flow decrease the total impedance in the cable. Thus, the heat loss and voltage drop as they are inversely proportional to the cable impedance. Shipboard DC distribution system, however, is still under consideration and has not been widely implemented yet. Some challenges to be solved including the size of power electronic converters, protection equipment, and protection coordination schemes [15]. Nevertheless, the possibility to apply DC shipboard distribution system is still being studied continuously as the advantages are very tempting. Ongoing research involves feasibility studies with current technologies and also development of the technologies to allow the implementation [16]–[18].

The reduction of power loss in DC distribution system could allow the reduction of generation powers from the power generators. The total powers generated by the generators are used to supply powers required by the electric load and to compensate the power losses on the grid. Lower required generation powers lead to the reduction of fuel consumption on the prime mover of the generator as the variable speed is allowed on the DC distribution system as the fixed frequency is not required [19]. Several studies record the fuel oil reduction around 20-30% by applying DC distribution system instead of AC system on a large ship [20], [21].

Most of the studies regarding the application of DC shipboard distribution system are focused on the medium voltage DC (MVDC) system as the MVDC has the lower electric current flows through the cable. However, some research also investigates the possibility of low voltage direct current (LVDC) distribution system with the result that LVDC can also save fuel around 10% compared to AC distribution system [22], [23]. Although the obtained fuel saving is not as much as in MVDC system, LVDC is easier to implement by directly replacing common low voltage alternate current (LVAC) system in the ship.

To decide if the LVDC distribution system is a feasible solution in shipboard, the reduction of fuel saving could not be the only parameter. Other factors such as installation cost and technical parameters including harmonic distortion and short-circuit current needs to be considered. The possible drawbacks such as the increase of short-circuit current and the protection capacity, as well as the increase of harmonics distortion and its filter compensation needs to be taken into account.

This study is focused to analyze the short-circuit current in LVDC distribution system applied on ship with non-electric propulsion. Even in the same level of short-circuit current, protection in DC system needs to be more sophisticated as there are no zero-crossing current, resulting possibilities of higher arc flash [24], [25]. Moreover, theoretically, the value of short-circuit current in DC distribution system is higher than in AC system as the impedance is lower [26]. Thus, the breaking capacity of the circuit breaker in the DC system may be higher than in AC system.

In this paper, the numerical simulation to investigate the short-circuit current in LVDC distribution system applied in a non-electric propulsion vessel is performed. The vessel data is taken from a tanker ship which originally use conventional AC radial distribution system. The aim of this study is to provide information of how is the short-circuit current of LVDC distribution system compared to LVAC system on the same load profile. The results of this study can be used as one of the factors to determine whether LVDC distribution system is worth to be used in a ship with a mechanical propulsion system.

The explanation of the procedure to obtain the value of short-circuit current: i) for both LVDC and LVAC systems is presented in the materials and method; ii) while the obtained results and the analysis are explained in the results and discussion section; and iii) The summary of the findings is expressed in the conclusion section.

2. RESEARCH METHOD

2.1. System overview

The study is performed on a sample vessel of 17,500 deadweight tonnage (DWT) oil tanker vessel. Tanker vessel is selected due to its higher average electrical load compared to other merchant ships [27]. Therefore, the impact of the energy savings will be higher to the fuel savings. Moreover, tanker vessel is only second to the general cargo vessels as the most available merchant fleet, numbered around 56,000 around the world [28]. The principal dimension of the sample vessel including the data of the generator is presented in Table 1. Three main generators are available on board.

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
teGenerator's voltage	V_g	450	V
Generator's frequency	f_g	60	Hz

The original electrical network system including the data of generators, networks, and loads are modeled in simulation software. The network consists of 37 electrical panels spread from the lowest part in the engine room to the top deck. The original network then reconfigured to the DC distribution system. The reconfiguration includes removing the step-down transformers from the 440 V feeder panels to the 220 V feeder panels in main switch board (MSB), adding the rectifiers between generator and the generator panels, as well as adding the inverters between feeder panels to the load panels. The generators and all the electric loads are not modified. The simplified one-line diagram of AC and DC distribution systems are presented in Figure 1(a) for AC system and Figure 1(b) for DC system.

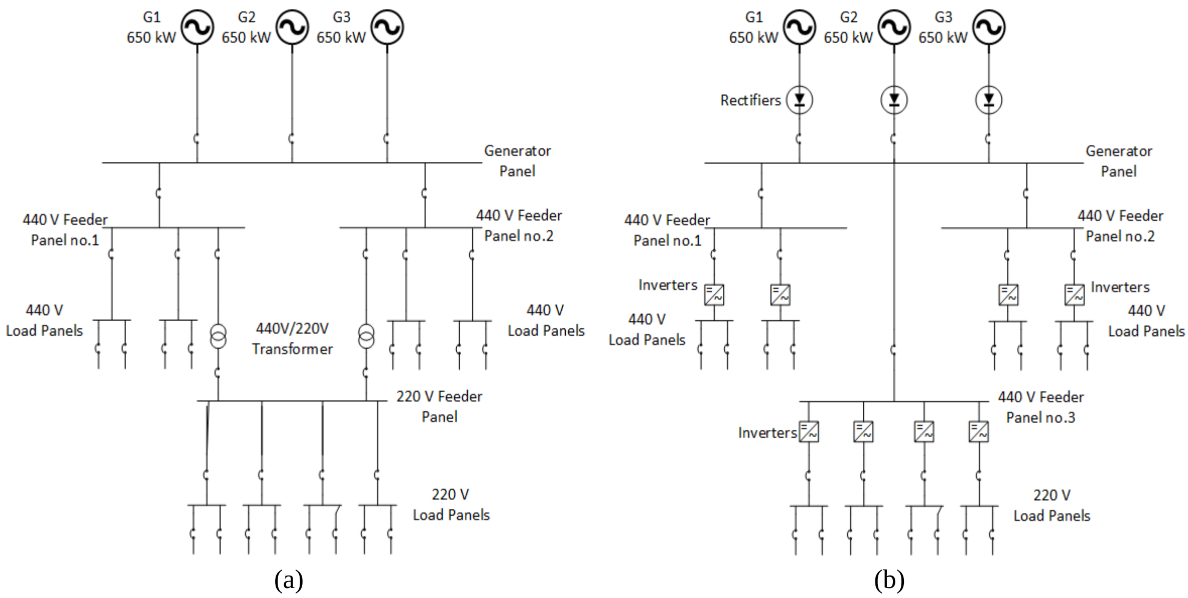

Figure 1. Simplified one-line diagram of the ship distribution system: (a) AC system and (b) DC system

The investigation of short-circuit of those two configurations are performed in four ship's operation modes. The operation modes include normal sea-going, leaving-arriving port, cargo unloading and at in port. Between them, cargo unloading required the most electric power with 1045.61 kW supplied by 2 generators. The comparison of the load profiles and number of operated generators between the four ship's operation modes is shown in Table 2. Compared with the other modes, the required power during cargo unloading is far higher due to the operation of 3×250 kW cargo pumps.

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

Ship's operation mode	Number of generators	Load consumption (kW)	Generators load factor (%)
Normal sea-going	1	547	84
Leaving-arriving port	2	532	41
Cargo unloading	2	1046	80
At in port	1	273	42

2.2. AC distribution system configuration

The original electrical system in the sample ship is arranged of LVAC system. All the devices from the generator, panels, cables, protection devices, and most of the loads are LVAC specified devices. Two level of voltages are applied in 440 V and 220 V with 60 Hz of frequency. Small portion of DC loads are used in examples for navigation equipment and failure alarms.

As shown in Figure, the main generation system consists of three diesel-powered generators with 650 kW capacity of each generator. The number and capacity of the main generators is designed to be able to supply electric power in all operating condition of the ships without additional supply from emergency source of electrical power, as regulated in The International Convention for the Safety of Life at Sea (SOLAS) chapter II-1/40.1.1 [29]. As the highest designed load is only 1046 kW, at most, even a pair of generators are sufficient to supply the load while the other one can act as a spare.

The generators which located in engine room are connected to generator panel located in engine control room. The generator panel is connected to two 440 V feeder panels which also located in engine control room. Most of the output branches of 440 V feeder panels are connected to the 440 V load electric loads while two output branches are connected to a 220 V feeder panel through two 440/220 V transformer and some other branches are connected directly to large motors. The 220 V feeder panel is connected to 220 V load panels which connected to some of three-phase loads and mostly single-phase loads.

The largest load on the ship, the three 250 kW cargo pumps are spread to two of 440 V feeder panels. Cargo pump no. 1 and no. 3 are connected to 440 V feeder panel no. 1 through floor no. 1 panel, while cargo pump no. 2 is connected to 440 V feeder panel no. 2 through floor no. 2 panel. All the pumps are designed to be operated simultaneously during cargo unloading. However, they are not to be operated during other operation modes. None of the loads other than cargo pumps are exceed 100 kW. The second highest load is a tank cleaning pump with 86 kW capacity. The tank cleaning pump is only operated during normal seagoing after the cargo are unloaded from the ship in the previous port.

The 220 V feeder panel mostly served single-phase loads. One of the most notable loads connected to the 220 V feeder panel are the lighting panels. There are seven lighting panels spread from the engine room to the top deck, with the total loads of 30 kW. The distribution line in this ship uses 3-lines cables without neutral cable. As a result, the single-phase loads are fed with 2 of phase cables instead of phase-neutral cable.

Two 440/220 V, 75 kVA transformer are used to connect power to the 220 V feeder panel. The first transformer is fed from 440 V feeder panel no. 1 while the second is fed from 440 V feeder panel no. 2. The two differences connection is designed to maintain the supply to 220 V feeder panel in case there is a problem in one of the 440 V feeder panel. The supply for 220 V feeder panel needs to be maintained as it is connected to essential navigation and communication panel located in navigation bridge deck. The navigation and communication panel are also connected to the emergency switch board supplied by emergency generator. The navigation and communication devices should be operable even during emergency condition such as blackout and dead ship. However, analysis during emergency condition is not performed in this study as the load profile is considerably smaller than in the other operation modes.

2.3. DC distribution system configuration

In this study, the original AC distribution system is converted to DC distribution system without replacing generators and the loads. The replacement is focused on the distribution equipment from the generator until load panels. The connections between load panels to the loads are left untouched.

To minimize the power loss and the number of rectifiers, AC to DC conversions is designed to take place between each generator to the generator panel. The rectifiers are designed to be placed in the MSB. Therefore, the bus bar in MSB needs to be replaced to DC-specified one, but the cables and circuit breakers between generator and the rectifier stay in their original specification.

All the devices between generator panel, 440 V feeder panels, and before load panels are replaced to DC-specified equipment, including the cables, circuit breakers, and the panels. The other notable change is the removal of the transformers as the transformers could not channels the power in DC lines. In the AC distribution system, the transformers are required to provide 220 V voltage to 220 V load panels through 220 V feeder panel. However, in DC distribution system, the voltage can be specified from the output of the inverter. Therefore, the original 220 V feeder panel is replaced to 440 V feeder panel no. 3 as there are no device to lower the voltage level from the generators. To reduce the cable and protection device, the 440 V feeder panel no. 3 is supplied directly from the generator panel instead of from the two lines of 440 V feeder panel no. 1 and no. 2 as in the original AC system.

To restore DC to AC voltage required by most of the loads, the inverters are installed before load panels. There are 10 inverters with various capacities, depend on the designed load operation connected to the related panel groups. There are 37 load panels spread in various locations in the ship and each inverter is served several panels which is located close to each other. The bus bars, incoming and outgoing circuit breakers, as well as the outgoing cables of the load panels stay in their original specifications. The output voltages of the inverters are set depend on the group of panels, either of 220 V or 440 V. The 60 Hz frequency also obtained from the inverter load. As the frequency is determined by the inverter, and there is no frequency required in DC lines between the generator to the inverters in load panels, the output frequency of the generators is not required to maintain at 60 Hz. Therefore, the generators can be operated in various speed that is the most economically optimum depends to the load profile.

2.4. Short-circuit analysis

Short-circuit currents need to be anticipated in all power systems, even in the small systems such as a household. Although the load capacity of a circuit breaker can be determined by the calculation of the designed nominal current, the breaking capacity of the breaker should be calculated based on the short-circuit current. When the breaking capacity of the breaker is less than the occurred short-circuit current, the breaker might not be able to trip and the large short-circuit current will continuously heat the cable and the devices, eventually lit the fire on the cables and components. Therefore, the selection of circuit breaker's breaking capacity needs to consider the maximum short circuit current flows on the respected line. In three-phase line, maximum short-circuit current occurs if all three phase cables are short-circuited. In single-phase line, it occurs when the phase and neutral cable are short- circuited [30].

The three-phase short circuit can be estimated by calculates the current from the generator and motor to the faulted bus panel through the impedances of cable, generator, and motor. Mathematically, the maximum short-circuit current can be calculated as (1)-(6).

$$I_f^{"} = I_g^{"} + I_m^{"} \tag{1}$$

$$I_g^{"} = \frac{E_g^{"}}{Z_g^{"}+Z_l^{"}} \tag{2}$$

$$I_m^{"} = \frac{E_m^{"}}{Z_m^{"}} \tag{3}$$

$$E_g^{"} = V_t + I_l Z_l^{"} \tag{4}$$

$$E_m^{"} = V_t - I_l Z_l^{"} \tag{5}$$

$$I_l = \frac{P_m}{\sqrt{3} V_t \cos\varphi} \tag{6}$$

In this study, maximum short-circuit current on all panels are analyzed. The analyses are performed both on original AC distribution system and the modified DC distribution system. In both systems, the analyses are performed for all panels consecutively, by set one panel to be short-circuited at a time. The objective of the analyses is to observe the change of short-circuit current when the system is modified to DC distribution system, especially to determine if the capacities of the circuit breakers need to be adjusted.

3. RESULTS AND DISCUSSIONS

In this section, the results of short-circuit simulations performed in both AC and DC distribution systems in the sample ship are presented. For each system, the short-circuit simulations are performed in all 37 electrical panels in 4 ship's operation modes. Three-phase short circuit is selected for the simulation to obtain the highest short-circuit so that the breaking capacity of the existing circuit breakers can be evaluated. However, before the short-circuit results are discussed, the load-flow simulations in both distribution models are also performed to justify if the reconfiguration to DC system can reduce the total power generated by the generators. The total power generated by the generators on each operation modes in both distribution system as presented in Table 3. The total power generated by the generators are calculated from the total power supplied to the load as well as the power dissipated on the distribution lines, including on cables, panels, and other equipment such as transformers and converters. The total power generated by the generators in the DC distribution system is unexpectedly higher than the AC system in all of operation modes, due to the losses in power electronic converters are higher than the reduction of losses in the cables.

Meanwhile, the short-circuit results during leaving-arriving port (LA) and cargo unloading (CU) are presented in the Table 4. Those two operation modes are given as samples as the loads are higher compared with the other two modes. For the same load panels in the same operation mode, the short-circuit current in the DC distribution system is lower than in AC system. There are two reasons of this phenom. First, in the AC distribution system, the total short-circuit current is the summation between real and imaginary current. However, the imaginary current is eliminated in the DC distribution system. Second, in the AC distribution system, when a bus of a load panel is faulted, that bus get the short-circuit current contribution from 3 directions, which are from the generators, from the motor connected to that panel, and from the motor connected to the other panels. Based on our simulation, when the same condition occurs in the DC distribution system, the current contribution from the other load panels is zero. The existence of the inverters blocks the reverse current from the motors in the other panels going through the faulted bus.

Table 3. 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 sea-going	1,061	1,120	553.4	841	1,196.6	1,400.8
Leaving-arriving port	1,205.4	1,208.1	618.3	907.2	1,354.68	1,510.89
Cargo unloading	1,205.4	1,271.7	618.3	955.2	1,354.68	1,590.42
At in port	520.4	549.5	291.3	412.7	596.38	687.22

Table 4. Comparisons of short-circuit current between AC and DC distribution system during leaving-arriving port and cargo unloading

No	Load panel group	V_{rating}	$I_{sc\text{-}LA\text{-}AC}$ (kA)	$I_{sc\text{-}CU\text{-}AC}$ (kA)	$I_{sc\text{-}LA\text{-}DC}$ (kA)	$I_{sc\text{-}CU\text{-}DC}$ (kA)
1	Floor no. 1	440	23.30	30.23	1.58	6.55
2	Vacuum pump	440	4.48	4.85	1.52	6.29
3	No. 1 DB E/R DB Purifier (MSB 440 V No. 1)	440	7.70	8.03	2.78	2.42
4	E/R 2nd Deck no. 1	440	18.91	22.98	4.63	2.62
5	Sewage treatment plan	440	15.25	17.57	4.33	2.53
6	No. 2 DB E/R DB workshop (MSB 440 V No. 1)	440	1.52	1.53	1.84	1.58
7	E/R 3rd deck no. 1	440	24.04	30.90	4.71	2.65
8	Fresh water hyd.	440	2.19	2.21	1.76	1.51
9	GSP 1	440	23.34	31.35	4.76	2.68
10	Incenerator	440	2.67	2.67	3.08	1.99
11	Accomodation vent. fan	440	2.20	2.23	1.43	1.18
12	Upper deck no. 1	440	22.83	28.98	1.97	1.59
13	Hyd. control valve	440	0.90	0.90	0.87	0.82
14	Air condition plant	440	16.79	19.83	1.93	1.60
15	Provision crane	440	4.94	5.09	1.89	1.57
16	Prov. refrigeration plan	440	3.50	3.57	0.19	0.19
17	Floor No. 2	440	23.29	29.94	1.16	3.52
18	Sanitary SW	440	2.61	2.64	1.05	2.48
19	E/R 2nd deck no. 2)	440	22.19	28.07	5.14	2.37
20	No. 1 DB E/R DB Purifier (MSB 440 V No. 2)	440	3.36	3.16	3.91	2.14
21	Thermal oil heater	440	22.76	28.59	5.21	2.37
22	GSP 2	440	24.03	30.78	5.28	2.42
23	E/R 3rd deck no. 2)	440	23.61	30.34	5.22	2.39
24	DB G-1 (MSB 440 V No. 2)	440	14.33	16.35	1.93	1.48
25	Upper deck no. 2	440	23.57	30.16	2.01	2.39
26	DB G-2 (MSB 220 V)	220	5.90	6.02	0.21	0.21
27	E/R 3rd deck 220 V	220	27.59	31.68	0.21	0.21
28	DB L-1	220	4.64	4.70	0.21	0.21
29	DB L-2	220	1.44	1.44	0.20	0.20
30	DB L-3	220	1.27	1.27	0.20	0.20
31	DB/ACC (MSB 220 V)	220	2.03	2.04	0.05	0.05
32	DB L-4	220	1.20	1.21	0.05	0.05
33	DB L- 5	220	0.98	0.99	0.05	0.05
34	DB L- 6	220	0.98	0.99	0.05	0.05
35	DB L- 7	220	0.98	0.99	0.05	0.05
36	ESB 440 V	450	22.00	27.69	0.32	0.18
37	ESB 220 V	220	2.42	2.45	0.53	0.34

Based on the simulation results, the highest possible short-circuit might occurred in the floor no. 1 load panel. during cargo unlading process. This result is to be anticipated as floor no. 1 panel is connected to two 250 kW cargo pumps. When short-circuit occurs in a panel, the panel receive current from the generator, the motors connected to the panel, and contribution current from the other motor through the distribution panel. As the floor no. 1 panel is connected to the biggest load, the panel receive high current from the cargo pumps.

Similar results are occurred on each of operation mode. The highest short-circuit are always occurs on the load panels that connected to the highest load at the correlated operation mode. For example, during normal sea-going mode, the highest short-circuit appears when short-circuit occurs on the floor no. 2 panel. The floor no. 2 panel is connected to the tank cleaning pump which is the highest operated load during normal sea-going mode.

The comparisons of average short-circuit current between two distribution systems for each operation mode are presented in Table 5. The short-circuit current in DC distribution system decreases about 10 times compared with in AC system. With the lower short-circuit current, the safety of the system is increased, and the specification of circuit breaker can be lowered.

The general advantage of the DC distribution system is that the power loss is decreases, resulting in lower fuel consumption of the generator. As the specification of circuit breaker can be lowered, it gives furthers advantage in the term of finance and easier for the maintenance. With the lower fuel consumption of the generator, the effect of carbon footprint may also be lowered.

Table 5. Comparison of average short-circuit current in AC and DC distribution system for each operation mode

Ship's operation mode	I_{SC-AC} (kA)	I_{SC-DC} (kA)
Normal sea-going	10.48	1.76
Leaving-arriving port	10.99	1.95
Cargo unloading	13.46	1.61
At in port	6.13	1.10

4. CONCLUSION

This paper aims to investigate the effect of short-circuit current value when the AC distribution system is modified into a DC distribution system in a conventional merchant ship. The short-circuit simulation has been performed in various load panels in both distribution systems. The results show that the short-circuit current can be decreased about 10 times when the DC distribution system is applied. The lower short-circuit current gives advantage in lowering the risk of fire and equipment damage and lowering the capital cost of the circuit breaker. More technical and economical aspect of the application of the DC distribution system in a conventional merchant ship needs to be investigated to complement the advantage in short-circuit current as presented in this paper.

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