Comparison of voltage harmonics in AC and DC shipboard electrical power distribution systems: A case study of 17,500 DWT tanker vessel

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Abstract. Recently, direct current (DC) shipboard electrical power distribution systems has begun to be looked at to replace conventional alternating current (AC) distribution systems. DC distribution systems has some technical advantages such as lower power losses and drop voltage across the distribution cables. However, there is a drawback in its high harmonics distortion due to the utilization of AC-DC rectifier in the generation side and DC-AC inverter in the load side. This study tries to investigate how much increase of voltage harmonics when a conventional AC shipboard electrical power distribution systems is replaced with equal DC systems. A 17,500 deadweight tonnage (DWT) shipboard systems is used as the case study. Both of AC and DC distribution systems are modelled with a same generation and load systems in a simulation software and the results are being compared. The comparison shows that DC distribution systems generate voltage harmonics are higher than AC distribution systems for the sample vessel.

1. Introduction
The increase in demand for crude oil shipping to distribute crude oil resulted in an increase in the number of tankers needed [1]. With the increasing number of tankers to meet market needs, it will increase the amount of fuel consumption. It can be seen that fuel is a non-renewable natural resource. As well as in determining the operational costs of fuel vessels is a very influential component [2]. With these problems, it is necessary to find a way to increase the efficiency of fuel use on ships so as to reduce ship operating costs and maintain natural sustainability.

Changes in the AC current distribution system to a DC current distribution system will eliminate the influence of the 50 Hz or 60 Hz frequency, so that losses that occur due to impedance in the cable can be eliminated [3]. And from the test results on the LNG-Tanker ship, it was found that the DC current distribution system is a solution for the future to increase the efficiency of fuel use in auxiliary engines on the ship [4]. The transition from an AC distribution system to a DC distribution system on ships is very tempting for the ship owner, this is based on the fact that the operational costs on the ship will decrease with the reduction of fuel consumption by auxiliary engines [3].

However, in changing the distribution system, there are several technical challenges, one of which is the prevention of harmonics in the system [5]. Changes in the DC distribution system will replace all distribution systems using DC, and the most important component of this DC distribution system
change is the use of rectifiers and inverters to change the current [4]. Rectifiers and inverters are components that can inject harmonic currents into the electrical system [6].

Harmonics in the electrical system can cause overheating of electrical components which can result in the equipment not being able to operate optimally or causing damage [7]. The Institute of Electrical and Electronics Engineers (IEEE) issued a standard in IEEE 519-2014 about limiting the occurrence of harmonics or total harmonic distortion (THD) in electrical systems less than 8% THD [8]. Based on these problems, it is necessary to analyze the harmonics of the reconfiguration of the DC distribution system to maximize performance and prevent rapid damage to the ship's electrical equipment. And in this study focuses on the analysis of the occurrence of harmonics due to the reconfiguration of the DC distribution system by taking the conditions on the tanker, and when the results of the harmonic analysis with THD are above the limits set by IEEE 519-2014, planning is carried out to reduce the harmonic distortion.

2. Method

2.1. Ship electrical system

The ship's electrical system is one of the systems on the ship that is used to deliver electrical energy for the sustainability of the operational performance of a ship. Without an electrical system on board, the ship will not be able to operate for operational activities. On ships, power plants generally use generators to meet the needs of all ship operational conditions. In determining the generator calculation, there are four ship operational conditions that must be met, namely, sailing, leaving/arriving port, loading-unloading and at port.

2.2. Reconfiguration of distribution system AC to DC

The ship's electrical distribution system is a system that functions to distribute electric power from a voltage source to the load. In general, the electrical system on ships uses AC current distribution, because the output from the generator is in AC current. However, reconfiguring the AC distribution system to DC can reduce the resistance that occurs due to impedance and can increase the efficiency of the use of generator fuel [4].

In reconfiguring the distribution system from AC to DC, power converter equipment, namely, rectifiers and inverters are important components [9]. Rectifier is a component to convert AC current to DC which in this reconfiguration is used to change the output of the AC generator. While the inverter, is used to convert the DC current into AC so that the loads are still supplied with AC current.

2.3. Harmonics distortion

Harmonics are electric waves whose frequency is an integer multiplication with the fundamental frequency [10]. When there is a superposition between the fundamental frequency wave and the harmonic frequency wave, a distorted wave is formed so that the waveform is no longer sinusoidal, this phenomenon is called harmonic distortion. Harmonic frequencies exist because there are sources of harmonics in the electrical system in the form of non-linear loads including, power converters, variable frequency drives, inverters, rectifiers, battery chargers, UPS, and DC motors [10].

Harmonics in an electrical system have a negative impact on equipment and cables carrying harmonic currents, so that overheating occurs quickly which can reduce the performance and efficiency of the equipment. In consideration of the IEEE limit the total harmonic distortion (THD) on the bus with the IEEE 519-2014.

3. Results and Discussion

After designing a single-line AC and DC diagram in the simulation software and determining the harmonic generation for each load that can inject harmonics, then a harmonic load flow simulation can be run to get the harmonic distortion results in the tanker electrical system. In Table 1 the results of the simulation show the magnitude of the total harmonic distortion (THD) that occurs and the location of
each bus. From the simulation results, it can be seen whether the harmonic distortion that occurs exceeds the standard limit or not.

| Table 1. Harmonic distortion of electrical system |
|-----------------------------------------------|
| Bus | kV | Sailing | Loading- | Unloading | Leaving/Arriving | At Port |
|     |    |         | Unloading |           |                |        |
|     | AC | DC     | AC       | DC        | AC             | DC     |
| Accomodation Vent Fan | 0.450 | 3,32 | 11,75 | 3,23 | 11,89 | 3,26 | 13,85 | 3,47 | 11,43 |
| Air Condition Plan | 0.450 | 3,31 | 11,71 | 3,22 | 11,85 | 3,25 | 13,80 | 3,46 | 11,39 |
| Bus 2nd Deck 1 | 0.450 | - | 15,95 | - | 14,12 | - | 16,12 | - | 13,57 |
| Bus 2nd Deck 2 | 0.450 | - | 16,11 | - | 11,28 | - | 16,25 | - | 10,60 |
| Bus 3rd Deck | 0.220 | - | 11,90 | - | 11,90 | - | 11,90 | - | 11,90 |
| Bus B Deck | 0.220 | - | 10,50 | - | 10,50 | - | 10,50 | - | 10,50 |
| Bus DB G-1 | 0.450 | 3,33 | 5,93 | 3,24 | 8,40 | 3,27 | 11,46 | 3,48 | 5,93 |
| Bus DB G-2 | 0.220 | 3,47 | 11,92 | 3,43 | 11,92 | 3,45 | 11,92 | 3,52 | 11,92 |
| Bus DB/ACC | 0.220 | 3,50 | 10,50 | 3,47 | 10,50 | 3,48 | 10,50 | 3,55 | 10,50 |
| Bus ESB 220V | 0.220 | 3,40 | 4,09 | 3,37 | 4,03 | 3,38 | 4,28 | 3,45 | 4,03 |
| Bus ESB 450V | 0.450 | 3,31 | 9,40 | 3,22 | 8,94 | 3,26 | 10,66 | 3,47 | 8,94 |
| Bus Floor 1 | 0.450 | - | 1,45 | - | 14,92 | - | 3,96 | - | 1,45 |
| Bus Floor 2 | 0.450 | - | 11,79 | - | 15,06 | - | 7,57 | - | 4,28 |
| Bus GSP NO.1 | 0.450 | 3,31 | 15,94 | 3,22 | 14,12 | 3,25 | 16,11 | 3,46 | 13,57 |
| Bus GSP NO. 02 | 0.450 | 3,31 | 16,10 | 3,22 | 11,28 | 3,25 | 16,24 | 3,46 | 10,60 |
| Bus Thermal Oil | 0.450 | 3,31 | 16,10 | 3,22 | 11,28 | 3,22 | 16,24 | 3,46 | 10,60 |
| Heater | | | | | | | | | |
| Bus Upper Deck 1 | 0.450 | - | 11,71 | - | 11,85 | - | 13,81 | - | 11,40 |
| Bus Upper Deck 2 | 0.450 | - | 5,92 | - | 8,39 | - | 11,47 | - | 5,92 |
| Bus179 (Generator 1) | 0.450 | 3,31 | 11,23 | 3,22 | 11,23 | 3,25 | 11,23 | 3,46 | 11,23 |
| Bus183 (Generator 2) | 0.450 | 3,31 | 11,23 | 3,22 | 11,23 | 3,25 | 11,23 | - | - |
| Bus190 (Generator 3) | 0.450 | - | - | 3,22 | 11,23 | 3,25 | 11,23 | - | - |
| E/R 2nd Deck No.1 | 0.450 | 3,31 | 15,95 | 3,22 | 14,12 | 3,25 | 16,12 | 3,47 | 13,58 |
| E/R 2nd Deck No. 2 | 0.450 | 3,31 | 16,11 | 3,22 | 11,28 | 3,25 | 16,25 | 3,47 | 10,61 |
| E/R 3rd Deck No. 1 | 0.450 | 3,31 | 15,95 | 3,22 | 14,12 | 3,25 | 16,12 | 3,46 | 13,57 |
| E/R 3rd Deck No. 2 | 0.450 | 3,31 | 16,11 | 3,22 | 11,28 | 3,25 | 16,25 | 3,47 | 10,61 |
| E/R 3rd Deck-220V | 0.450 | 3,31 | 11,79 | 3,21 | 15,06 | 3,25 | 7,57 | 3,46 | 4,28 |
| Floor No. 1 | 0.450 | 3,31 | 1,45 | 3,20 | 14,90 | 3,25 | 3,96 | 3,46 | 1,45 |
| Floor No. 2 | 0.450 | 3,31 | 11,79 | 3,21 | 15,06 | 3,25 | 7,57 | 3,46 | 4,28 |
| Fresh Water Hyd | 0.450 | 3,33 | 16,06 | 3,24 | 14,22 | 3,27 | 16,23 | 3,48 | 13,67 |
| Hyd. Control Valve | 0.450 | 3,33 | 11,77 | 3,24 | 11,91 | 3,27 | 13,88 | 3,48 | 11,46 |
| Incenerator | 0.450 | 3,34 | 16,02 | 3,22 | 14,12 | 3,26 | 16,13 | 3,46 | 13,58 |
| NO.1 DB E/R (DB Purifier) | 0.450 | 3,31 | 16,12 | 3,22 | 11,28 | 3,26 | 16,26 | 3,46 | 10,60 |
| NO.01 DB E/R DB Purifier | 0.450 | 3,33 | 16,06 | 3,22 | 14,12 | 3,28 | 16,23 | 3,46 | 13,58 |
| NO. 1 FO Purifier | 0.450 | 3,34 | 16,10 | 3,22 | - | 3,28 | 16,27 | 3,46 | 13,58 |
| NO. 1 LO Purifier | 0.450 | 3,34 | 16,09 | 3,22 | - | 3,28 | 16,26 | 3,46 | 13,58 |
| NO.2 DB E/R (DB Workship) | 0.450 | 3,34 | 16,04 | 3,24 | 14,20 | 3,28 | 16,21 | 3,49 | 13,65 |
| Prov. Refrigeration | 0.450 | 3,33 | 17,52 | 3,23 | 17,52 | 3,27 | 17,52 | 3,48 | 17,52 |
From the results of the harmonic simulation in Table 1, the change in the distribution system from an AC distribution system to a DC distribution system has a large effect on the value of the harmonic distortion. In the AC distribution system, the THD that occurs in every operational condition of the ship on each bus does not exceed the standard limit of IEEE 519-2014, although in the AC distribution system there are several sources of harmonics such as fluorescent lamps and transformers that can inject harmonic currents. Meanwhile, in DC distribution system, the harmonic distortion that occurs increases in each bus when compared to the AC distribution system. The THD on the DC distribution system in every ship operating condition also exceeds the standard limit of 8% from IEEE 519-2014.

The effect of reconfiguring the AC distribution system into DC increases the harmonic distortion that occurs in the tanker's electrical system. The addition of converter equipment for reconfiguration of the distribution system causes the harmonic distortion to become larger. The converter equipment in the DC distribution system in the form of rectifiers and inverters is a non-linear load that can inject large harmonic currents. Therefore, the DC distribution system needs to be improved to reduce harmonic disturbances by installing a harmonic filter on the DC distribution system.

4. Conclusion
Reconfiguration of the AC distribution system to DC on tankers raises several technical challenges that need to be overcome, one of which is harmonic distortion. The addition of converters in the DC distribution system results in an increase in harmonic distortion that occurs. This is evidenced from the simulation results with THD on AC conditions on the bus generator panel of 3.31% THD on sailing conditions and 11.23% THD on DC distribution system with the largest THD on Prov. Refrigeration Plan of 17.52% THD. One of the possible solution to fix the harmonic disturbance that exceeds the standard is by installing a single-tuned passive filter on the DC distribution system.

References
[1] Kersing, A., Saxon, S., & Xie, Q. (2020, November 30). Data will decide success in the next normal of bulk and tanker shipping. McKinsey & Company [Online]. Available: https://www.mckinsey.com/industries/travel-logistics-and-infrastructure/our-insights/data-will-decide-success-in-the-next-normal-of-bulk-and-tanker-shipping#.
[2] Zahedi, B., Norum, L. E., & Ludvigsen, K. B. (2013, November). Optimization of fuel consumption in shipboard power systems. In IECON 2013-39th Annual Conference of the IEEE Industrial Electronics Society (pp. 1124-1129). IEEE.
[3] H. Tessarolo, A., Castellani, S., Menis, R., & Sulligoi, G. (2013, April). Electric generation technologies for all-electric ships with Medium-Voltage DC power distribution systems. In 2013 IEEE Electric Ship Technologies Symposium (ESTS) (pp. 275-281). IEEE.
[4] Javaid, U., Dujic, D., & Van Der Merwe, W. (2015, November). MVDC marine electrical distribution: Are we ready?. In IECION 2015-41st Annual Conference of the IEEE Industrial
Electronics Society (pp. 000823-000828). IEEE.

[5] Liu, H., Liang, J., & Qi, L. (2015, September). *Harmonics mitigation and stability analysis of DTC motor drives in MVDC systems*. In 2015 IEEE Energy Conversion Congress and Exposition (ECCE) (pp. 3172-3178). IEEE.

[6] Wakileh, G. J. (2001). Power systems harmonics: fundamentals, analysis and filter design. Springer Science & Business Media.

[7] Tariq, M., & Iqbal, M. T. (2014). Power quality improvement by using multi-pulse AC-DC converters for DC drives: Modeling, simulation and its digital implementation. Journal of Electrical Systems and Information Technology, 1(3), 255-265.

[8] "IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems," in IEEE Std 519-2014 (Revision of IEEE Std 519-1992), vol., no., pp.1-29, 11 June 2014

[9] Prenc, R., Cuculić, A., & Baumgartner, I. (2016). Advantages of using a DC power system on board ship. Pomorski zbornik, 52(1), 83-97.

[10] Francisco, C. (2017). Harmonics, power systems, and smart grids. CRC Press.