DC secondary distribution grids on future naval ships: a comparison with conventional AC distribution systems and their safety aspects

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Synopsis

Naval ships can use energy storage systems for the transition towards zero-emission technologies. The generation, storage and propulsion devices are connected to a DC grid to increase energy efficiency. However, smaller consumers and hotel loads throughout the ship are connected via a low-voltage AC distribution grid.
A DC distribution grid is expected to be more energy efficient, lighter and smaller than a conventional AC distribution grid. This paper aims to quantify the potential benefits of using a DC distribution grid and identify the risks of this new technology.
A conventional AC distribution grid design is compared with an equivalent DC distribution grid design for a typical surface combatant use case. Aspects included are energy efficiency, weight and footprint. Then, this paper delves into the various aspects affected by the choice of earthing, including common-mode voltages and currents, which can lead to electromagnetic interference.
It was shown that a DC distribution grid can save up to 25 tons of weight and 28 square meters of space for the specific use case. The energy losses are expected to be a factor of 2.5 less. Various earthing strategies, such as those involving the midpoint or negative terminal of the grid, yield different sets of advantages and disadvantages in terms of safety and availability. Unlike the relatively straightforward choices regarding the earthing strategy of the neutral point in AC grids, determining the best approach for the midpoint of DC grids is less obvious. It is shown that there is no earthing approach that gives the optimal solution for all investigated aspects. The adoption of new grid topologies brings about both advantages and risks. This paper elucidates the rationale behind these changes and underscores the importance of considering associated risks, particularly emphasizing the role of earthing. If the risks are properly mitigated, a DC distribution grid can be an improvement compared to a conventional AC distribution grid.

Keywords: DC distribution; Naval; Earthing; Energy Efficiency

1. Introduction

More and more naval ships use energy storage systems for the transition towards zero-emission technologies. Hybrid ships are gaining ground because of the integration of alternative sources such as methanol engines and fuel cells (Haxhiu, 2022). The generation, storage and propulsion devices can be connected to a DC grid to increase energy efficiency. However, the distribution grid usually remains AC because of the variety of loads and conservative design choices.

A full DC ship can potentially save costs and improve energy efficiency (Piazza, 2018). Additionally, using a DC distribution grid saves valuable space onboard of the ship. Besides, the availability of DC loads and components is increasing, making DC distribution a viable option. Most AC loads have an internal AC to DC conversion step anyway. DC distribution grids are upcoming. Applications are already found in office buildings, electric vehicles, smart cities, infrastructure projects and data centres (Dragičević, 2018). There are some challenges in the design of a ship's DC distribution grid. At this moment, there is no maturity in maritime standards that provide guidance in DC topics such as voltage level, grounding and power quality (Latorre, 2023; Xu, 2022). Also, it is not clear how much energy efficiency, weight and space can be saved.

This paper aims to tackle the above issues. The goal is to quantify the potential benefits of using a DC distribution grid and to identify the risks of this new technology. This is done by finding an answer to the following questions:

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- What is the benefit of using a DC instead of an AC distribution grid in terms of weight, energy efficiency and space?
- What are the possibilities of connecting AC consumers to a DC grid?
- How should the main and distribution DC grids be connected in terms of earthing?
- What other considerations need to be addressed in terms of earthing?

To answer the first question, Chapter 2 compares a conventional AC distribution grid design with an equivalent DC distribution grid design for a typical surface combatant use case. This chapter also addresses the second research question regarding the loads.

Then, in chapter 3, this paper delves into the various aspects affected by the choice of earthing, including common-mode voltages and currents, which can lead to electromagnetic interference. Given the presence of multiple power converters in a DC grid, which act as common-mode current sources, it is crucial to focus on mitigating this phenomenon.

Finally, chapter 4 draws a conclusion.

2. Quantitative Comparison Between an AC and a DC Distribution Grid

This chapter compares an AC distribution grid to a DC distribution grid. The use case consists of a fictional navy ship with a DC propulsion grid and four secondary distribution grids. Each distribution grid has different types of loads connected to it. The comparison is made by evaluating the difference in efficiency, weight and footprint of the components and loads. The boundaries of the evaluation are the connection terminals to the main DC grid and the connection points of the loads.

2.1 Use case

Figure 1 shows the simplified single line diagrams of the AC and DC use cases. Each of the four distribution grids has a rated power of 1 MW. The distribution grids are connected to a 1000 VDC main grid. The 440 VAC grids are connected with a 690 VAC grid converter, filter, cables and a transformer. The 700 VDC grids are connected with an isolated DC/DC converter.

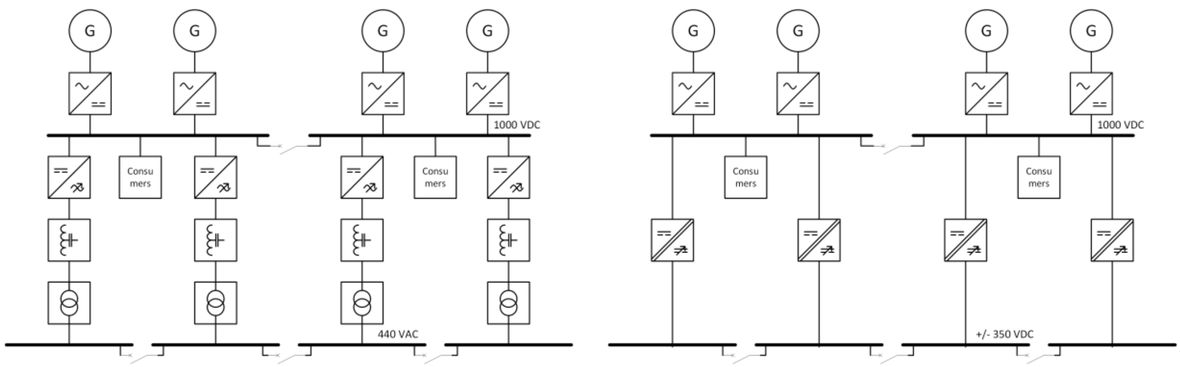

Figure 1: Single line diagram of the use cases. An AC (left) and DC (right) distribution.

The voltages for DC distribution grids on ships are not defined yet in standards. However, the electrical engineering community seems to converge to the voltages given in Table 1. The DC voltages are chosen so that:

1. they are doubled for every level,
2. they are different from the AC voltages so there is no confusion,
3. they are higher than the AC peak for that same level so the DC voltage can supply the AC consumer and
4. the highest level (1400 VDC) is lower that the threshold value for “high voltage” (1500 VDC), because for high voltage, different standards apply.

Table 1: DC grid voltage levels. The voltage for the DC distribution grid is chosen to be +/- 350 V for flexibility.

AC (RMS)	AC (peak)	DC equivalent	Unit
115	163	175	V
230	325	350	V
400	566	700	V

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440	622		
690	976	1400	V

2.2 Components

This section discusses the grid components that are in between the propulsion grid and the connection points of the consumers for both the AC and the DC case. For every component, the efficiency, weight and volume are estimated. The following components are considered:

- grid converters,
- transformers and
- cables.

2.2.1 Grid converters

As will be discussed in chapter 3, galvanic isolation is necessary between the sections of the distribution grid. The grid transformer in an AC grid provides this isolation, but a DC/DC conversion step doesn't need a transformer. Therefore, a DC/DC grid converter with galvanic isolation is needed in the DC distribution grid. A major advantage of these converters is that the isolation happens in a high frequency transformer. These transformers are much smaller than the 50 or 60 Hz grid transformers. However, the demand for high power isolated DC/DC converters is recent. There are not many types on the market (yet). At this moment, the technology is mainly pushed by the electric vehicle market for fast charging. The assumptions for the grid converters are shown in Table 2.

Table 2: Assumed grid converters based on manufacturer data. The DC/AC conversion step consists of one large 1 MW unit, the DC/DC conversion step consists of several parallel 75 kW units.

	Parallel modules	Efficiency	Weight [kg]	Size [mm]
DC / AC	1	97 %	180	375 x 505 x 924
Isolated DC / DC	14	98.5 %	50	496 x 502 x 174

2.2.2 Transformers

There are transformers in the AC distribution grid. In the conversion step from the DC propulsion grid to the 440 VAC distribution grids there are four 1250 kVA transformers through which all the load on the distribution side is supplied. Then, on a lower level, every load centre is connected through one or two transformers which ensure the right voltage and an additional level of galvanic isolation. Some of the consumers are connected to the 440 VAC grid directly, so their loads only flow through one of the four large grid transformers. For the DC case, it is assumed that 20% of the loads still need to be connected to AC by means of an inverter and a transformer. Table 3 shows the assumed efficiency and weight (including cabinets and LC filter) of the transformers based on manufacturer data. The total footprint (including space around it) of the 1250 kVA grid transformer is assumed to be 9 m^2.

Table 3: Transformers in the AC and DC distribution cases

Voltage	Efficiency	Rating	Weight	Amount (AC)	Amount (DC)
115 VAC	98.5 %	30 kVA	275 kg	4	0
		20 kVA	230 kg	8	0
230 VAC	98.5 %	100 kVA	575 kg	2	0
		60 kVA	450 kg	4	0
		40 kVA	300 kg	4	0
		20 kVA	230 kg	4	4
		5 kVA	100 kg	8	0
440 VAC	98.5 %	100 kVA	575 kg	4	0
440 VAC	97.5 %	1250 kVA	3850 kg	4	0

2.2.3 Cables

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The cables that connect the DC distribution switchboards to the main switchboard can be laid directly from the DC/DC converter (which is in the switchboard of the main grid) to the distribution grids. The cables in the AC case first go to the transformer and then to distribution switchboards, meaning they are longer. The assumptions based on manufacturer data are shown in Table 4.

Table 4: Cable parameters for the AC and DC distribution cases

	AC primary	**AC secondary**	**DC distribution**	**unit**
Length	40	10	40	m
Area	120	50	95	mm^2
Number of parallel conductors	8	9	7	
Resistance at room temp.	387	387	193	mΩ/m
Nominal current	240	153	209	A
Weight	4.85	2.17	3.76	kg/m
Efficiency at rated power	96	96	97.6	%

The cables are sized for the nominal power. For the analysis, the operational power is used. The conductor temperature dependent resistance, $R(T)$, of the cables is considered as follows:

$$T = T_0 + dT\left(\frac{I}{I_{nom}N_p}\right)^2$$

$$R(T) = R_0(1 + \alpha(T - T_0))$$

where T_0 is the ambient temperature, dT is the maximum allowable temperature difference, I is the conductor current, I_{nom} is the conductor current, N_p is the number of parallel conductors, R_0 is the resistance at ambient temperature and α is the temperature coefficient of copper. The nominal current is derived from the nominal power of the distribution grids.

2.3 Consumers

For every consumer, an assumption is made to which voltage point it is connected. With this information it is possible to determine the distribution efficiency per consumer for the AC distribution case. To find the distribution efficiency for the DC case, it must be known which consumer connects to which voltage. To make a generalization for the consumers, they are grouped as follows:

- motors,
- heaters,
- lighting,
- rack equipment and
- general equipment.

An assumption of the amount of consumed power during operation per group is shown in Figure 2. The grid components are sized for the nominal power.

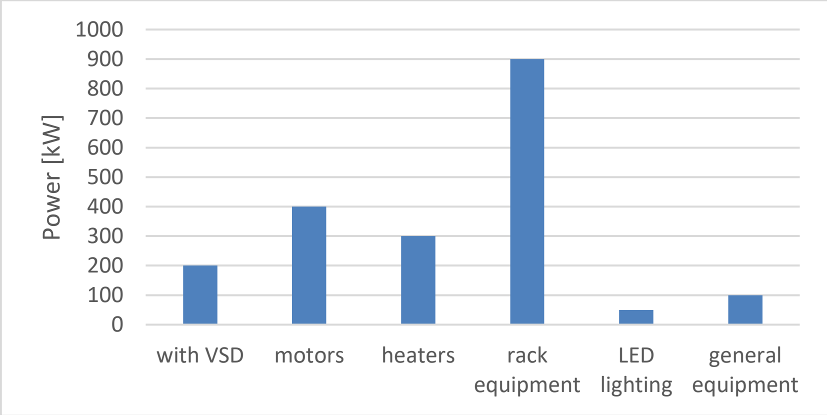

Figure 2: Assumed operational power use of the use-case. Rack equipment which includes weapon and radar systems.

In this section, every group is addressed. For every group it is discussed if it is possible to connect it to DC and what the implications and assumptions are.

2.3.1 Motors

Motors are either connected through a Variable Speed Drive (VSD), a Direct On-Line (DOL) or a soft-starter. For the AC case, most of the motors are connected with a DOL or soft starter. For the DC case, all the motors need to be connected with a VSD, which adds more losses. Connecting a VSD to DC is more efficient than to AC. For AC, the voltage is first rectified to DC, and then a three-phase variable frequency voltage is created. When a VSD is connected to DC, the rectifier step can be bypassed. An efficiency of 97.5 % is assumed for a VSD that is connected to AC and 98.5 % for a VSD that is connected to DC. DOL's and soft starters are assumed to have an efficiency of 100 %.

2.3.2 Heaters

A large part of the consumers consists of heaters which are used in HVAC, water treatment or other auxiliary systems. In this research, it is assumed that all the heaters are able to be connected to DC. On a technical level, this shouldn't be a problem. However, in practice it means that the suppliers of the systems that use heaters should reconsider their designs.

2.3.3 Lighting

The general lighting on the ship is LED. A LED driver is connected to the 230 VAC which converts the 230 VAC to a 24-48 VDC that powers the LEDs. A LED driver has a typical efficiency of 85 %. In the case of a DC distribution grid, the LEDs can be connected directly to the local 24 or 48 VDC connection points without LED driver losses (USDOE, 2013). The weight and volume of the LED driver are assumed to be negligible.

2.3.4 Rack equipment

A large part of the rack equipment consists of servers which are powered by 400/230 VAC. Datacentres are already moving towards DC distribution grids because the benefits are significant (Sterlace, 2020; Miller, 2016). The power supply cabinets that power other parts of equipment are designed to transform 440 VAC to another workable voltage. These cabinets can be redesigned to transform the 700 V DC voltage to another workable voltage. In this study it is assumed that all the 440 VAC cabinets and racks can be converted to DC. For the 400/230 VAC equipment it is assumed that 20 % still needs to be powered by an AC source.

2.3.5 General equipment

The general equipment category consists of bakery, galley, laundry, workshop, office etc. For this equipment it is assumed that most of it can be turned into DC by ordering specialized equipment. 20% of this load is still considered to be 400/230 VAC.

2.4 Results

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Table 5 shows the results for the weight comparison between the AC and DC grids. It can be seen that most weight is saved due to the lack of grid transformers. The need for more converters adds more weight to the DC grid.

Table 5: Results of the weight comparison.

	AC [tons]	DC [tons]	Difference [tons]
Grid transformers	15.40	0	15.40
Small transformers	11.01	1.15	9.86
Cables	6.99	4.21	2.78
Drives	0.72	3.28	-2.56
Sum	31.65	8.89	25.48

The power dissipation in the AC and DC distribution grids is shown in Table 6. The results are based on the load profile which is defined in Figure 2. The DC distribution system is more than a factor 2.5 more efficient than the AC distribution system. The savings make up ~5% of the total power for a specific mode of operation.

Table 6: Losses in both the AC and DC distribution grids and loads.

Total power [kW]	Losses AC [kW]	Losses DC [kW]	Savings [kW]
1950	156	63	93

The lack of distribution transformers also has an impact on the total footprint of the distribution system. It is expected that an extra area of 36 m2 is available because of this. However, the extra drives which are needed in the DC distribution system are expected to take up to 8 m2 of space. The volume and area savings for the rest of the components is found to be insignificant.

3. Earthing considerations

Earthing plays an important role in an electrical installation. It influences its safety and functional behaviour. The choices may benefit one aspect but deteriorate another. That is why it is important to have a clear understanding of what influences earthing. Only if all impacts are known, it is possible to weigh pros and cons to make the best choice. This chapter discusses the most significant aspects related to earthing. Three different main aspects of earthing can be identified:

- Protective earthing, to prevent that accessible non-live parts can have a dangerous potential due to fault conditions, static electricity or leakage currents.
- System earthing determines whether a live part of the installation is connected to earth and where the protective earth is connected to earth in the system. In a Terra Neutral Separate (TN-S) system, the neutral point, midpoint or minus is connected to earth and the Protective Earth (PE) conductor is connected to that point. In an Isolated Terra (IT) grid, there is no intentional connection between a live part and earth, the PE conductor is locally connected to earth.
- Electro-Magnetic Compatibility (EMC) earthing or equipotential bonding.

3.1 Electrocution

Electrocution risks should be minimised by the proper application of insulation materials and protective earthing. The safest configuration of a DC network if a person would come into contact with a live conductor depends on a few aspects:

- Is there a ripple voltage present on the DC and what is the level and frequency of that ripple voltage?
- What is the capacitance to earth?
- Are there suitable DC residual current detectors (RCD) available?

If there are RCDs available, a TN-S approach is preferred since, in case of a leakage current, the voltage will be switched off immediately. Also, only 50% (2 wire system) or 66.6% (3 wire system) of the power conductors are at a dangerous potential, reducing the chance of touching a dangerous live conductor. In an IT grid all conductors are at a dangerous potential. If there is no RCD available and either the voltage ripple on the grid is low or the capacitance to earth is very low and an IT grid is less dangerous. Since an IT grid has no connection between a live part and earth, there is no obvious current loop created when a person touches a single live conductor. However, there might be filter capacitors connected to earth in the grid, and there will certainly be a parasitic capacitance between the grid and earth. In combination with a voltage ripple (which is usually significantly higher than 60 Hz) this enables a potentially dangerous current. Notion should be given to the fact that for higher frequencies the human body is less sensitive to exposure to currents (IEC 60479-2, 2019).

With high capacitance values, the least dangerous option is the TN-S grid since the chance on to coming into contact with a live conductor at a dangerous potential is smaller. In an IT grid touching any conductor will result in a discharge of all capacitance to earth in that grid.

3.2 Arc flash

From an arc flash point of view, an IT grid is a safer solution. The chance of a fault to earth is significantly higher than a fault between lines. In an IT grid, there is no short circuit in case of a single earth fault. In a TN-S grid there is. This could result in an arc. However, if an RCD is available, the risk is somewhat reduced since such a device should interrupt an earth-fault current within 40 ms if the fault current is 5 to 10 times the nominal current. If a protection system is used that will switch of the voltage before sufficient energy is released in an arc, there is no disadvantage in applying TN-S grids.

3.3 Fire hazard

Fires can be easily ignited by leakage currents even as low as 300 mA (IEC 60755-1, 2022). In a TN-S grid with suitable RCDs this risk is mitigated. Even TN-S grids without RCDs are relatively safe, since an earth fault will often result in a short circuit, triggering the breaker or fuse. IT grids have a higher risk of fire. They are designed to stay operational under single earth fault conditions. If a high enough ripple on the DC occurs and there is sufficient capacitance to earth, the impedance can be sufficiently low to conduct a fault current. This current will flow as long as the earth fault is there, which can be days. Also, faults are often not continuous connections but due to vibration on board. The fault is continuously made and interrupted resulting in sparks since the capacitance between earth and line is discharged every time the earth fault is made and recharged when the connection is broken.

3.4 Availability

The availability of system plays an important role. An IT system continues to be operational under single earth fault conditions, contrary to TN-S systems. So, from continuity of supply point of view it is better to use IT systems. However, an insulation monitoring system should be installed that indicates where the fault can be found, else significant parts of the installation might have to be switched off to localize the fault. Critical systems should not just rely on continuity of supply but should be built with redundant components where each component can be powered from multiple power sources.

3.5 Signature

A naval ship's signature should be minimised including its (electro)magnetic signature. In both grid configurations TN-S or IT, there shouldn't be a DC current flowing through the hull. In a TN-S grid, such a current could flow under single fault conditions if the current is too low to trip a safety device. This is the case for faults with a high impedance. In IT grids there are two faults required. If these faults are in the same line, the currents flowing through the hull could be much higher and no safety device will trip.

AC common mode currents are much more likely to flow through the hull, especially in TN-S grids where filters are applied to control common mode disturbance. In IT grids, the capacitance to earth (in filters) is minimised, but in practice there is still a lot of capacitance to earth enabling AC common mode current to flow through the hull. To summarise, a well maintained, properly designed IT grid, has a smaller signature then a TN-S grid.

3.6 Galvanic corrosion

Galvanic corrosion can be increased where current exits a metal into an electrolyte. DC is known to speed up galvanic corrosion, but also AC has an effect (Bergin, 2015). These currents can be common-mode currents or fault currents though the hull. The grid configuration has influence on the current level through the structural parts and hence on the level of galvanic corrosion.

The aspects that determine the amount of current that flow through structural parts is already discussed in section 3.5, but it is also important where the current flows through the structural parts. Only currents that exits the metal speeds up the corrosion. From that point of view, AC currents are less of a concern because their path is determined by impedance. Especially common mode currents, which usually have a higher frequency, will flow in the smallest loop possible since that path has the lowest impedance. DC currents will concentrate in the path with the lowest resistance, and it is quite likely that the hull is part of this current path since the thick steel offers a low resistance. Both types of grid configuration TN-S and IT could work well under the condition that for:

1. TN-S grids, residual current detectors are applied, if there is a leakage current below the tripping level it is small and the ratio between the resistance of the hull and that of sea water will reduce any current leaving the hull even further.
2. IT grids, earth faults are repaired immediately because two earth faults in the same line can result in very high current levels flowing through the hull and then still a significant level could leave the hull and speed up corrosion.

3.7 Electromagnetic compatibility

Below deck common mode currents are one of the main sources of interference. Capacitors to earth will improve both aspects, with their low impedance for higher frequencies they lower the common mode voltage on the grid and by placing the capacitors in the right positions, the size of common mode current loops can be decreased. To be allowed to use multiple capacitors to earth, a TN-S grid is preferred since in an IT grid the capacitance to earth should be minimised.

4. Conclusions

This paper aims to give insight in the use of a DC distribution grid instead of an AC distribution grid. The gain in efficiency, weight and footprint in using a DC distribution grid instead of an AC distribution grid is quantified. For a particular use-case it was shown that the use of a DC distribution grid approximately saves 93 kW of power, 25 tons of weight and 28 m^2 of space. The biggest difference is because there is no need for AC grid transformers in DC. DC still needs galvanic isolation in the DC/DC converters, but the high frequency transformers are more compact. Many of the loads are expected to be ready to be connected to a DC grid.

Assuming that soon DC RCDs and monitoring devices will be readily available, there is no clear preference for TN-S / or IT grids in general. This does not mean that the topic of power grid configuration is unimportant, but rather that it depends on priorities and additional measures. Table 7 shows the evaluated phenomena related to the grid's topology. "+" indicates if, from safety or reliability point of view, the grid's topology gives a good match with the considered phenomenon and "-" indicates that the match between phenomenon and grid's topology is less favourable.

Table 7: Preferred choice of grid topology

Phenomenon	TN-S	IT
Electrocution	++-	---
Arc flash	+--	+++
Fire hazard	+++	+--
Availability	+--	+++
Signature	+--	++-
Galvanic corrosion	++-	++-
Electromagnetic interference	+++	++-*

* Under the condition that the applied earth fault insulation monitors can deal with the present capacitance to earth.

In conclusion, both grid topologies can work satisfactorily if the proper measures are taken to compensate for disadvantages.

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