Power System Design Considerations for a Seafloor Mining Vehicle

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***Abstract* — The main goal of this paper is to give a framework for designing the power distribution system for seafloor mining vehicles operating in deep and ultra-deep waters. As the starting point prior to the design, the tethered seafloor mining vehicles are compared with their counterparts in the terrestrial mines and the well-developed remotely operated vehicles. Then, various power distribution alternatives are studied and compared taking into account the main design criteria such as efficiency and size of components. Although the major loads of these vehicles are AC motor loads for drilling, pumping and locomotion, it is concluded that the DC distribution, both in topside and subsea sections, is the best option. Typical values for efficiency and volume grades (normalized values) for the major components in the distribution system have been considered in the calculations.**

Keywords— AC power distribution, DC power distribution, Deep-sea mining, Medium frequency AC, ROV, Subsea vehicle, Submarine dynamic cable.

I. Introduction

Large-scale seafloor mining is a reality that belongs to the future perspective of the mining industry and currently it is in the technological development phase [1]. The focus of this paper is on the seafloor heavy vehicles employed to collect polymetallic Manganese Nodules (MN) and excavate Seafloor Massive Sulfide (SMS) deposits. MNs are rocks, with 1-10 cm diameter, spread over vast areas of the ocean floor in depths of 4-6 km [2]. The MN mining vehicles collect the nodules, possibly crush them inside their containers and then pump them to a topside vessel; hence, there is no need for drilling in hyperbaric conditions. On the other hand, SMS deposits exist in underwater volcanic areas in shallower waters (1.5-4 km). SMS deposits excavation is conceptually similar to the open-pit terrestrial mines. Researchers and companies have proposed different scenarios for SMS mining and their discussion is still ongoing. The two better-defined ones are:

- Three remotely seafloor vehicles are involved in preparing the ores to be transported to the surface by a subsea pump, as in the solution implemented by Nautilus Minerals company [1, 3].
- A large trench-cutter is deployed to drill vertically and store the ores in a transportable storage container as proposed by Bauer Group [4].

In general, more power is required for SMS excavation, due to drilling, than collecting MNs. As a reference, if the MN collector operates in 500 m water depth, it requires 180 kW electric power [2], while the power requirement of an SMS mining vehicle designed for 2.5 km water depth can be as high as 2.5 MW [3].

The supporting vessel for ocean floor mining should be equipped with Dynamic Positioning (DP). In addition, it should have sufficient space for the ores pre-processing equipment and their storage until another vessel transport them to shore. The power generation capacity of the Nautilus Minerals' supporting vessel is higher than 30 MW for their project in Solwara 1.

Although deep-sea mining is a rather new concept, there are two well-developed technologies, which are in some ways similar to the seafloor mining vehicles: terrestrial mining machines and Remotely Operated Vehicles (ROV) operating in marine environment. Their knowledge can be helpful in the design process of subsea mining. Due to the similarities between the mining processes, the behavior of loads in both terrestrial and subsea mining can be similar. In addition, gathering information about work-class ROVs is helpful to recognize the electrical and mechanical challenges in subsea environment and to become familiar with the state-of-the-art of the power distribution systems mounted on them. In this paper, their common challenges, similarities and differences will be explained in sections II and III, respectively.

There are only a few scientific contributions on the deep-sea mining from its energy demand perspective. There are relevant information about MNs mining process in [2]. For the SMS deposits, [4] and [5] clarify some aspects of the aforementioned mining scenarios including their power demand. Ref. [6] investigates Alternating Current (AC) and Direct Current (DC) power distribution alternatives for SMS mining for a possible project in the Norwegian Sea with a specific water depth and power demand assumptions. However, the literature lacks a general design approach for such vehicles operating in various depths, which will be the covered in this paper.

Operating in subsea environment makes the components design challenging from both electrical and mechanical perspectives and it is likely to make trade-off decisions in order to meet the technical requirements in this process. This makes the comparison among the possible designed candidates very difficult and usually qualitative. Therefore, it is important to be able to take all the determining factors into account, quantify their significance (i.e. defining grades based on their priorities) to be able to compare them with better

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accuracy. In section IV, a design flowchart will be proposed considering combinations of AC with 50/60 Hz frequency, Medium Frequency AC (MFAC), e.g. 400 Hz frequency and DC for both topside and subsea distribution systems. Then, they will be compared by having compactness and efficiency as the main design criteria. Since designing such systems necessitates considering more factors such as guaranteeing safety, maximizing reliability and reducing project costs, the proposed methodology is able to get extended to include them as well.

II. TERRESTRIAL VS. SEAFLOOR MINING

The knowledge of the power distribution in the terrestrial mining is advantageous when assessing possibilities for supplying electrical power to the seafloor mining vehicles. The SMS mining can be very similar to the onshore open-pit mines. However, the major difference between them is of course related to their environments, particularly the pressure and the temperature of the mining location. According to [7], the cutting forces needed to crack the rocks are 4 to 6 times higher in 180 bar (equivalent to 1800 m water depth) than in the atmospheric conditions. Therefore, seafloor mining vehicles require significantly more energy than their corresponding onshore ones to do their missions in high hydrostatic pressure. Moreover, the temperature of the deep areas is low (around 1 °C), while it can be as high as 350 °C near the hot water springs.

Subsea mines operate with isolated grids similar to the onshore mines in remote areas. In addition, the subsea mines are low accessible; hence, it is more probable to build their power distribution systems radially, similar to the underground mines. This is in contrast with the recommendation of having ring distribution on the onshore open-pit mines which increases the system reliability [8]. Hence, the reliability at the component level should be maximized by designing them with fault tolerant performance.

Furthermore, the power distribution system of the terrestrial mines are traditionally AC, while there has been a tendency toward DC in recent years, due to the wider development of frequency converters [9, 10]. Consequently, it would be wise to investigate the DC alternatives for subsea mines as well.

The missions of their mining equipment such as drilling, crushing and loading (or pumping) of deposits are somehow similar. There are also smaller loads for additional purposes including traction, vertical and horizontal displacement of the arms and auxiliary systems e.g. for control and communication. These vehicles can be all-electric or electrohydraulic (using Hydraulic Power Unit or HPU for part of the valves, arms and manipulators). However, the focus of this paper is aligned with the trend that is toward all-electric solutions due to their faster response time, higher power density, higher efficiency and lower maintenance rate [11, 12]. Moreover, the load profile of seafloor mining vehicles can have similar pattern as their corresponding onshore ones, which are usually very cyclic and extremely varying [8, 13, 14]. This is mainly due to the pattern of their repetitive missions. The operation of a large land excavator can vary surprisingly between 200 % motoring mode to 100 % regenerating mode in one-minute interval [13]. Furthermore, it is reported in [15] that a shovel can have 15 % regeneration during each operation cycle in average. While an accurate estimation of the regenerative braking energy for a seafloor vehicle is out of scope of this paper, according to [16], the regenerative braking energy of a thruster in water is half of its value in air. It can be concluded that in pressurized subsea environment, the regeneration energy would be even less than that.

Moreover, in contrary to the open-pit mines, there are strict weight and especially size (volume) restrictions applied to the subsea components, and they become even more important if the components are mounted on the vehicles.

III. ROVS VS. SEAFLOOR MINING VEHICLES

Seafloor mining vehicles can be considered as non-buoyant ROVs that are able to perform complex tasks by remote operators or autonomously. They are both able to work in the marine environment and fed by power umbilicals. However, ROVs consume less power than seafloor mining vehicles to perform lighter missions such as inspection, sampling, repair and maintenance of the offshore structures. A typical value for installed power of a work-class ROV is in the range of 100-300 kW.

In ROV design, the compactness constraint is highly prioritized and it is common to see that the other constraints such as efficiency and voltage drop at the cable terminal, are relaxed compared to the volume and weight of its onboard components [17]. However, the high power consumption levels of the mining vehicles, especially those excavating SMS, urge the designers to have the efficiency as a major design concern as well.

Since the accurate positioning of buoyant ROVs is their essential goal to perform their missions successfully, the cable tension forces on the vehicle should be minimized. This goal can be fulfilled by reducing the cable weight and diameter and/or using a combination of a Tether Management System (TMS) and a neutrally buoyant tether. However, these constraints have lower priority for a seafloor mining vehicle, because its submerged weight should be large enough to keep its position stable on the seafloor even during drilling periods.

The distribution systems mounted on ROVs are either AC or DC and the transmission voltage is usually MFAC (400-800 Hz) [16-19] or DC [20]. In [19], AC, DC and MFAC distribution system has been compared for a 100 kVA ROV with a 10 km long cable and their advantageous and disadvantages have been listed. The authors conclude that MFAC is better than the low-risk AC due to its lower weight and faster start-ups with the expense of greater voltage drop. In addition, the DC distribution has higher design and reliability risk, while eliminating one copper conductor leads to save cable cost and weight.

TMS can also contribute to hold a part of power distribution system; for instance in [21], the step down MF transformer is assembled on the TMS. The industry orientation is shifting from hydroelectric ROVs toward the all-electric ones due to the aforementioned reasons. Consequently, for choosing a proper distribution system for a seafloor-mining vehicle, both AC, MFAC and DC solutions should be investigated having in mind the possibility of a power hub (i.e. the TMS in the ROV case). Knowing the state-of-the-art in the heavy-duty work lass ROVs can be helpful in understanding the major issues and challenges in the underwater environment although their applications are different.

IV. Power Distribution Design Framework

In this section, the design of power distribution system feeding seafloor mining vehicles is explained. Needless to say that the top design priorities are always safety and reliability, but they are out of scope of this article. The main design criteria covered here are compactness and efficiency. All the possible radial distribution alternatives will be taken into account and compared based on their efficiency and size estimations.

The power distribution system can be classified into two main categories: topside and subsea (power umbilical and seafloor equipment). The power components involved in each category are selected and arranged by taking all the design constraints into account in iterative processes.

The proposed design flowchart is shown in Fig. 1. At the configuration evaluation stage, the user defines the primary inputs, including vehicle mission, number and type of loads (AC or DC), maximum depth of operation and the electrical and mechanical upper and lower limits. After selecting the desired distribution onboard the vessel, the subsea distribution voltage level and type should be selected. The boundaries can be drawn for AC (50 Hz), MFAC (400 Hz) and DC for medium voltage range as illustrated in Fig. 2. This figure is useful at the initial phase of the power system design. By having an estimation of the total power demand and depth of operation (or cable length) for the seafloor vehicle, the voltage

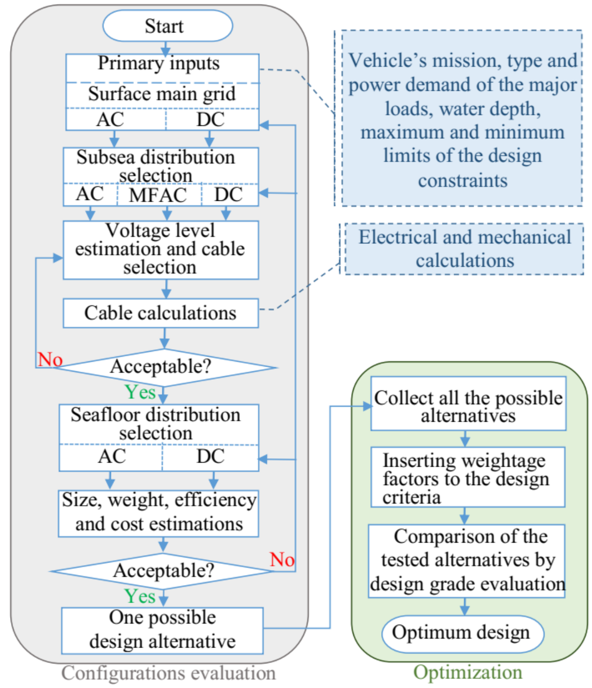


Fig. 1 The design flowchart for the power distribution system.

level and type can be selected. The curves are depicted considering voltage drop (10 %) and cable loading limitations (50-80 %) on the standard 1.9/3.3 kV and 3.8/6.6 kV cables with cross-sections 25-400 mm^2 for each phase presented in [22]. Increasing frequency from 50 to 400 Hz causes high voltage drop at the cable terminal that pushes the boundaries to the left (smaller distances) in contrast with the DC distribution that covers larger distances. The designer can modify these constraints and Fig. 2 would be modified accordingly. The final part of the configuration evaluation stage is to select a proper seafloor distribution system. The final product is a proper alternative that satisfies all the predefined design constraints.

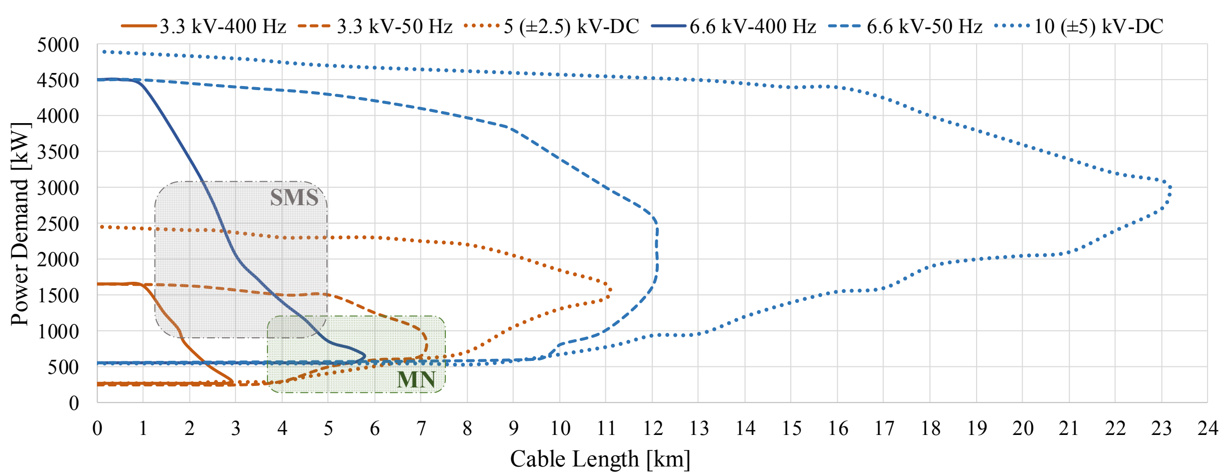


Fig. 2 The boundaries for the MV distribution voltages: AC (50 Hz and 400 Hz) and DC. The maximum allowed voltage drop is 10% (limiting the curvy parts of the boundaries) and the cables are loaded between 50% (limiting the lower part of the curves) and 80% (limiting the upper part of the curves). The colored boundaries indicate approximate areas for MN and SMS mining vehicles.

Then at the optimization stage, the most suitable alternative can be chosen by applying a comparison method among all the evaluated configurations to reveal their strengths and weaknesses. The main purpose of this stage is to make the alternatives comparable by grading or quantifying the design priorities. A radar (spider) diagram that has several axes can be an appropriate tool to visualize all the important design factors such as mechanical and electrical properties including efficiency, components weight and volume. It can be used beneficially for comparison purposes by making the strengths and weaknesses of each alternative very clear. The area surrounded by each alternative will be associated to the design grade that implies its suitability qualitatively. The authors have applied this method to the umbilical selection procedure for subsea vehicles in [23]. Hence, it is not going to be repeated here.

A. *Primary Assumptions*

Although the physical characteristics of the commercialized components are usually customized and depend mainly on the component power and voltage ratings, normalized values for their volume and typical values for their efficiency would be helpful for the comparison of the evaluated alternatives.

Table I gives information about commercialized components in the medium voltage range. The efficiency of the transformer is assumed to be equal to 99 % (the same as Resibloc ABB dry transformers [24]). ABB's ACS2000 and Alle Bradley's Power Flex 7000 are medium voltage AC drives (AC/AC) and their rated efficiency are 97.5 % in the case of having Active Front End (AFE) rectification [25, 26]. If these motor drives have an integrated input transformer, their efficiency will be reduced to 96.5 % (multiplication of the typical efficiencies of the transformer and the AC/AC drive) as shown in Table I. This value can be as low as 95 % for the ABB's low-voltage static frequency converter for marine applications, PCS100 [27].

The effect of adding the input transformer to the converter cabinet on its size and weight can be observed in [25] by comparing them, with and without integrated transformers, in the medium voltage range (6.6 kV). It can be concluded that for high power applications (≥1 MW) adding a transformer to the converter cabinet will approximately double its weight and volume. It is assumed that the weight and volume of the DC/AC motor drive is 60 % of the corresponding AC/AC drive and its efficiency is the same as ABB's PSV800, 98.5 % [28].

MF transformers (MFT) have not been commercialized yet and are still in the development phase. In [29], A 3-MW MFT operating in 500 Hz has been designed with efficiency and size equal to 99.78 % and 0.5 m^3, respectively which is included in Table I as well.

Table I. Converters, transformers and battery specifications

Components	Power	Voltage [kV]	η [%]	V [m^3]	Weight [kg]	Ref.
AC/AC drive	615 [kW]	6.6:6.6	97.5	4.1	1550	[25]
	1760 [kW]	6.6:6.6	97.5	7.2	2550	[25]
AC/AC drive + integrated Transformer	615 [kW]	6.6:6.6	96.5[a]	8.1	3450	[25]
	1760 [kW]	6.6:6.6	96.5[a]	12.4	5940	[25]
Transformer (T)	3150 [kVA]	20:0.4	99	6.8	7800	[24]
MFT (500 Hz)	3000 [kW]	33:3.3	99.78	0.5	2009	[29]
Battery	46×4 [kW]	0.23	NA	1.2	1900	[30]

[a] These values are calculated.

B. *Topside and Subsea Considerations*

Depending on the topside grid voltage (MVAC or MVDC), the onboard power equipment involved in supplying power to the seafloor vehicles varies.

It is recommended that all the loads be fed via a galvanic isolation device in ships power systems [31]. The reason behind it is to increase safety, protect the equipment and detect ground faults. Transformers, preferably compact MFTs, are used for this purpose. In this paper, the configurations are designed having galvanic isolation on the topside power system.

The link between the topside vessel and the seafloor mining equipment is a dynamic power cable (umbilical) that is responsible to transfer not only electrical power but also the control, communication and measurement signals to the loads via integrated optical fibers. Since all the metallic parts of portable equipment connected to the ship power system should be grounded, there should also be a grounded conductor integrated in the cable [31]. The cable should be designed carefully considering both electrical and mechanical limitations. The electrical properties to be considered are maximum allowed voltage drop at the cable terminal, thermal limits of the cable in special locations e.g. the middle layer of the wounded cable around its drum or inside bend stiffeners and joints. However, mechanical considerations are of greater importance since this cable is portable which makes it vulnerable to the mechanical stresses imposed from the ocean conditions (waves and currents) and mobility of the mining vehicle. Therefore, it should be designed carefully to have adequate mechanical strength and torque balance. It is recommended to have double helix steel armoring wrapped in opposite directions on such dynamic submarine cables [32].

From the power perspective, larger cross-section of cable improves the efficiency and the voltage drop at the cable terminal, while it has a negative impact on the vertical (i.e. top tension due to weight increase) and horizontal (i.e. drag forces due to diameter increase) forces acting on the cable [23]. Therefore, the cable diameter and weight should be optimized. The cable diameter can be reduced by feeding the vehicle electrically (or removing the hydraulic fluid from the umbilical), using a single multicore cable, selecting a proper distribution voltage and increasing the overall system efficiency.

Generally, a DC cable has higher power transfer capability than an equivalent AC one, as illustrated in Fig. 2, because of both voltage and current enhancement (elimination of skin and proximity effects). The cable is able to tolerate DC line-to-line voltage equal to the peak of AC line voltage continuously. It has been stated in [33] that the insulation of AC cables are designed considering a safety margin (called headroom factor) and this value can be reduced for DC voltages due to their static electric field. In this case, 47 % higher DC voltage can be applied to the AC cable that increases its power transfer capability accordingly [33]. In this study, it has not been considered.

The information given in Table II points out the superiority of the DC cable as well. AC, MFAC and DC voltages are applied to the same cable (95 mm^2 copper conductor for each phase) that feeds a 2 MW load in 3.5 km distance. The cable data of [22] have been used (for 3.8/6.6 kV), while the operating temperature of the cable is assumed 65°C. The DC voltage is equal to the twice of the peak phase voltage. The cable loading, voltage drop (V_{drop}), power loss (P_{loss}) and reactive power (Q) circulated in the cable are the compared parameters. As expected, the power loss and voltage drop are highest in 400 Hz and lowest in the DC one. The AC resistance is almost equal to the DC one in 50 Hz if the conductor's area is below 240 mm^2 (copper skin depth in 50 Hz is 9.3 mm), which is usually enough for the seafloor mining vehicles. However, if the frequency increase to 400 Hz the skin depth will be 65 % reduced that leads to having higher values for the AC resistance for conductor areas larger than 35 mm^2.

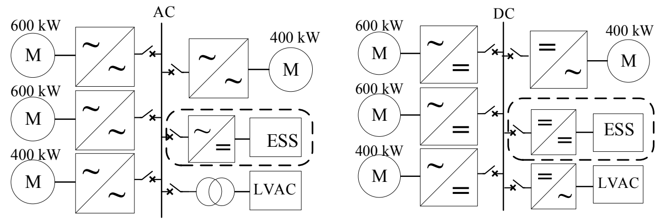
It is worth mentioning the importance of symmetry in the dynamic cable design to minimize the torsional forces. As a result, if one conductor is eliminated in the DC cable case, fillers should fill its space and as a result, the diameter would likely remain the same. Nevertheless, the cable weight will be reduced dramatically. One conductor with 95 mm^2 area and 3.5 km length weighs more than 7 tons.

The seafloor loads, which are the last part of the power distribution chain, can be categorized into MV loads and Low Voltage (LV) loads. Dual-bus topologies for both MV and LV loads provide high redundancy if there is enough space for that. The MV loads are either induction motors or permanent magnet synchronous motors for vehicle positioning, drilling, crushing and pumping the deposits. The LV loads (e.g. 400-600 V) are the auxiliary loads for controlling the converters, commissioning, lighting, video recording, etc. It is assumed that they require 10 % of the maximum power demand.

The distribution distance is relatively short (< 5 km); however, it is not feasible to feed several motor loads on the vehicles with topside converters due to the cables power loss, diameter and weight increase [6]. Therefore, the use of subsea

Table II. Testing various medium voltage distribution voltage for the same load (which could be an SMS mining vehicle) and cable.

Properties	Voltage [kV]	Loading [%]	V_{drop} [%]	P_{loss} [kW]	Q [kVAr]
AC (50 Hz)	6.6	83	4.5	96	24
AC (400 Hz)	6.6	91	14.2	189	280
DC (bipole)	±5.4	78	2.8	56	0



(a) (b)

Fig. 3 Seafloor AC distribution (a) and DC distribution (b) and the connected loads in a maximum loading situation for an SMS mining vehicle similar to Auxiliary Cutter. The dashed line means that the equipment is optional.

TABLE III. The typical values of efficiency and volume grades of both High-Power (HP) and Low-Power (LP) components. Most of the values have been assumed based on the realistic data given in Table I.

Component	AC/DC	AC/AC	T	MFT	DC/DC	DAB
Efficiency (η) [%]	98.5	97.5	99	99.5	99	96
HP volume grades	0.6	1	1	0.1	0.3	0.5
LP volume grades	0.3	0.5	0.5	-	0.15	-

Table IIIV. The efficiency and volume grade of the proposed seafloor AC and DC distributions shown in Fig. 3 based on values of Table II.

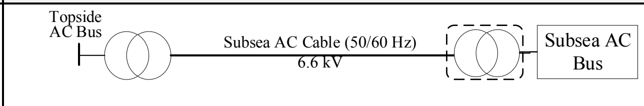
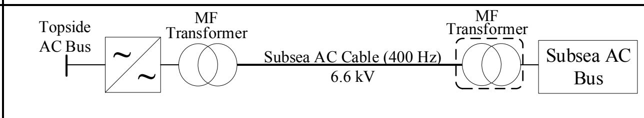
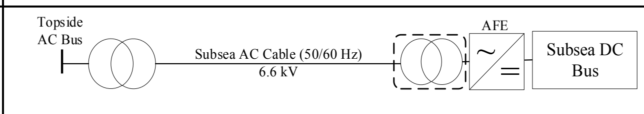
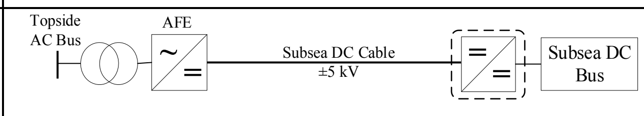
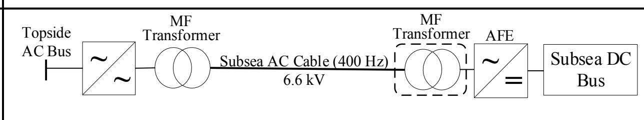
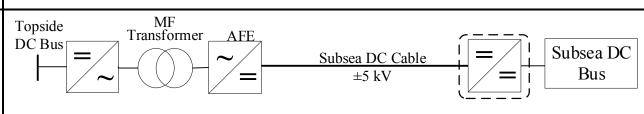
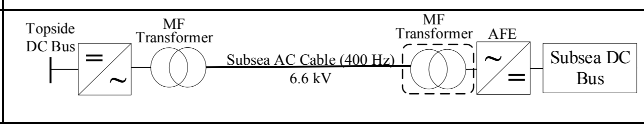
Seafloor main bus	Efficiency	Volume grade
MVAC	95.6 %	2.8
MVDC	97.7 %	1.7

converters in the oil-filled pressurized canisters is necessary in the distribution system picture. The technology of the frequency converters operating under pressure up to 300 bar has been already developed [34, 35]. The boundaries of the distribution voltage can be pushed to higher values in order to eliminate the intermediate subsea components (transformers or converters) that step down the voltage.

Fig. 3 illustrates two alternatives for seafloor distribution system considering both AC and DC for a typical SMS mining vehicle. For the sake of simplicity, only a single bus has been shown in this figure. It is assumed that the vehicle is all-electric and the maximum power demand occurs when four major loads are running simultaneously including cutter heads (600 kW), pumping motor (600 kW), crushing motor (400 kW) and other loads such as arm positioning and traction (400 kW). In total, they consume 2 MW simultaneously.

Considering the realistic data given in Table I, it is beneficial to set typical values (as given in Table III) for efficiency of various components and apply volume grades to them in order to be able to compare them. Therefore, the total efficiency of the DC distribution is 97.7 %, two percent more than the AC one (Table IV). The overall size and weight of the components are mainly determined by the volume grades of Low-Power (LP) components given in Table III. The overall size and weight of the AC common bus, excluding the motors, circuit breakers, battery module and LV loads, would be approximately 65 % larger than the corresponded DC one

TABLE IV The possible radial power distribution systems feeding a seafloor mining vehicle including their efficiency and volume grades. The dashed lines surrounded optional components. The light gray rows correspond to the case including the optional components, while they are excluded in the white rows. TS and SF stand for topside and seafloor equipment.

No	TS	Cable	SF	Power Distribution Configurations	Topside volume grade	Subsea volume grade [a]	Total volume grade	Efficiency (η) [%] [b]
1	AC	AC	AC		1	3.8	4.8	89.5
						2.8	3.8	90.4
2	AC	MFAC	AC		1.1	2.9	4	82.2
						2.8	3.9	82.6
3	AC	AC	DC		1	3.3	4.3	89.6
						2.3	3.3	90.5
4	AC	DC	DC		1.6	2	3.6	90.3
						1.7	3.3	91.2
5	AC	MFAC	DC		1.1	2.4	3.5	82.4
						2.3	3.4	82.8
6	**DC**	**DC**	**DC**		**0.5**	**2**	**2.5**	**89.3**
						1.7	**2.2**	**90.2**
7	DC	MFAC	DC		0.7	2.4	3.1	84.1
						2.3	3	84.5

[a] The cable volume is not included. [b] The cable efficiency is included.

(Table IV). Therefore, it makes more sense to use DC distribution for the seafloor loads as well. However, AC distribution may be preferred in some projects due to the commercialized and available components in the market.

In addition to the components shown in Fig. 3, there should be ground fault, over current and over voltage detection circuits. The best alternatives for interrupting DC short circuits for subsea applications would be the solid-state or hybrid circuit breakers [36]. In addition, there should be a mechanism to control the overvoltage caused by the regenerative energy of the motor loads during braking intervals. This energy can be dissipated in a resistor or recovered and restored in an energy storage system (ESS). The integration of battery modules on the ROVs, its advantages and disadvantageous have been explained in [37, 38]. Despite all the advantages of ESS such as recovering the motors regeneration energy (efficiency improvement), providing energy during fast transients and peak shaving to smoothen the large variations of power profile, they can be spacious. For example, if pressure-tolerant subsea battery modules (lithium-ion or polymer lithium-ion batteries [39]) are used to supply 10 % of the total demand, they will occupy at least 1.2 m^3 and the dry weight will be 2300 kg (the specifications are given in Table I). Another challenge that should be investigated about installation of lithium batteries for the seafloor vehicles is related to their poor performance in very cold environment.

It should be mentioned that the seafloor distribution system can be either mounted on the mining vehicle itself or assembled as a power hub near the mining location (on the seafloor or on a buoyant structure similar to TMS) or a combination of these scenarios. The mobility of the MN mining vehicles leads to not consider a fixed-position power hub for them. However, the SMS mining equipment will stay in a region for longer periods and building seafloor power hubs for them would be reasonable especially when the number of cables and/or their diameter should be excessively increased due to very high power demand or parallel operation of multiple vehicles.

C. The Overall Power Distribution System

The onboard grid on the supporting vessel is whether AC or DC. The subsea power can be fed via the power umbilical with AC, MFAC or DC voltage. Finally, the seafloor distribution can be either AC or DC. In total, there are twelve combinations. However, some of them are not reasonable due to the unnecessary number of conversion stages which are neglected. Table V presents seven most probable radial configurations to feed a seafloor vehicle mining vehicle.

There are HP subsea components (transformers or converters) surrounded by dashed lines to indicate that they are optional. Usually the subsea converters and motors in the discussed power range are operating with voltages equal or less than 3.3 kV. If higher voltage level (6.6 kV_{AC} or 10 kV_{DC}) is desired to save the space, those components can be eliminated. However, increasing the voltage makes the design more challenging in addition to penalty of delivering unregulated bus voltage oscillating continuously depending the loading situation.

It is assumed that the bidirectional Active Front End (AFE) rectifiers rectify the voltage in all the configurations, due to their advanced control capabilities especially their ability in improving the voltage profile without bulky harmonic filters. It is possible to replace them by the low-cost and robust unidirectional diode rectifiers (at least 12 pulse); however, their performance is not optimized regarding Total Harmonic Distortion (THD) and power factor, they occupy more space (due to the input transformers), have no control on the DC link voltage and regeneration recovery capability [40].

The least space would be occupied by the DC-DC-DC (6) and then the DC-MFAC-DC (7) subsea distributions. It has been mentioned earlier that DC is also a winner configuration in the seafloor distribution. Therefore, the configuration number 6 (DC-DC-DC) is the best regarding both topside and subsea volume grade. Even if Dual Active Bridge (DAB) is used instead of the simple buck converter in the configuration, the subsea volume grade will remain minimum among the other ones. Its efficiency is among the highest values and only one percent lower than the most efficient configuration, AC-DC-DC (4). However, this configuration occupies the topside space more than all the other alternatives (three times larger than configuration 6).

If the main grid on the vessel is AC, the topside volume occupation will be almost the same for all the alternatives except the one that provides DC voltage for the subsea equipment that is 50 % more (due to the isolator transformer).

Except configurations 1 and 3, there is a frequency converter that feeds the subsea distribution system from the vessel main grid. There are concerns regarding the amount of harmonics injected by this converter to the subsea distribution system that may trigger the resonance frequency of the power cable and create noise interference into the signals to be transmitted by optical fibers [41]. Therefore, appropriate filtering strategies preferably by active filtering (to save space) or passive filters should be applied to mitigate them and obviously filtering the DC voltage would be much easier.

V. Conclusions

The depletion of terrestrial mines and the dramatic metal demand growth will inevitably lead to exploit the underwater mines with high production rate in future. In this paper, seafloor mining process and the involved equipment have been explained briefly. There are two well-developed technologies that have been compared with the subsea mining: land-based mines and ROVs. The seafloor vehicles have been compared with the land excavators and ROVs from electrical power perspective to clarify their similarities and differences. However, the main contribution of this study is to propose a generalized design approach for the power distribution system of the seafloor mining vehicles that is especially useful at the feasibility study of projects.

Although the main design criteria covered in this work are the compactness and efficiency, it is possible to include more constraints into the picture. The AC (50 Hz), MFAC (400 Hz) and DC power distribution alternatives have been compared. From the cable point of view, DC voltage provides more efficient power transfer with the lowest voltage drop as expected. In addition, the cable would be lighter and smaller in diameter that is a remarkable advantage from the mechanical forces perspective. In general, the DC distribution (both topside and subsea) is the best option regarding its size. However, its overall efficiency is one percent lower than the most efficient alternative that is the one with AC topside and DC subsea.

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