

Investigation of AC and DC Power Distributions to Seafloor Mining Equipment

Razieh Nejadi Fard and Elisabetta Tedeschi
 Department of Electrical Power Engineering
 Norwegian University of Science and Technology Trondheim, Norway
 razieh.nejadi@ntnu.no, elisabetta.tedeschi@ntnu.no

Abstract — The main goal of this paper is to study and compare different power distribution alternatives for subsea electrical components for deep-sea mining in the Norwegian Sea. Such application requires power delivery in the multi-MW range at water depth of more than 3000 m. Hence, AC (50Hz), DC, high frequency AC and low frequency AC can be possible options to transfer electrical power to the mining equipment. Comparing them at the preliminary stages of projects is beneficial in order to select the most suitable alternative. Minimizing voltage drop and distribution losses, in addition to reducing the number of components, their weight and cost are critical and often conflicting aspects, to design the electrical system appropriately. In this paper, the basic processes of deep-sea mining (regarding Seafloor Massive Sulfides) will be described briefly. In addition, an estimation of the amount of required power to feed the subsea mining equipment for the Norwegian Sea case will be given and finally, different power distribution schemes will be analyzed and compared, using the PowerFactory/DIGSILENT software for simulations.

Keywords—Deep-Sea Mining, Seafloor Massive Sulfides, AC power distribution, DC power distribution, Subsea power system.

I. INTRODUCTION

More than 70% of the earth surface is covered with water, while the geological structure is the same as land areas having mountains, valleys, flat plains and even volcanic regions. Therefore, the mineral properties of offshore areas can be similar to the onshore ones. However, because of the technical, legal and environmental challenges regarding mining the oceans floor, this has not been done in large scale yet.

The most important mineral resources, that have been found on the seabed, are: Seafloor Massive Sulfides (SMS) [1], Manganese nodules [2] and Cobalt-rich crusts [3]. The focus of this paper is to analyze various AC and DC power systems to feed the SMS miners.

Seafloor Massive Sulfides (SMS) are created in volcanically active regions on the seafloor due to the movement (especially divergence) of tectonic plates along each other [4]. Acidic high temperature (up to 450°C [5]) fluids exit the seafloor fissures and mix with low temperature ambient seawater (1-4 °C); subsequently metal sulfides precipitation occurs around the opening fissure. The deposit accumulation forms chimney-shaped structures called hydrothermal vents. An active hydrothermal vent may collapse over time and become inactive. Active and inactive hydrothermal vents have been



Figure 1: Loki's Castle location in the Norwegian Sea

found at mid-ocean ridges (65%) and also in back-arc basins and on submarine volcanic arcs (35%) [6]. They exist mostly in water depth between 1500 to 3500 m but a few of them exist in shallower and ultra-deep waters up to 4000m [1].

SMS deposits typically contain precious metals such as copper, zinc, silver and gold. The global amount of SMS deposits has been estimated around 600 million tons containing 30 million tons copper and zinc [7].

Although SMS deposits took attentions in 1970s for their high metal concentration[8], rather low metal prices and technological difficulties of mass excavation in hyperbaric conditions made it economically unviable [3].

However, due to the earth population growth, fast transition through industrialization, in the developing countries, and technology development, Deep-Sea Mining (DSM) is going to become feasible in near future.

Northern Mid-Atlantic Ridge (NMAR) is a host for many active and inactive hydrothermal vents considered as possible mining sites [9]. There is a well-known active hydrothermal vent named Loki's Castle (73°33'N,08°09'E) located in the Norwegian Sea in 2400 m water depth [10]. This location has been selected as a reference site for data and sample collection for the validation of properties relevant for mining activities on an active hydrothermal vent site. The operational mining

depth is assumed up to 3000 m, considering the possibility of expanding the mining site to deeper areas, while the design depth for the equipment and cable length is assumed 3500 m. In section II, mining process will be explained.

The structure of this paper is as follows: the required amount of power, to put DSM into action, will be given in section III and various power distribution configurations, to feed subsea mining equipment, including AC and DC, will be introduced in section IV. Section V contains simulation results and the related discussion regarding configurations comparison. Finally, conclusion will be presented in section VI.

II. DEEP-SEA MINING PROCESS

From the technical point of view, the most challenging part of DSM is excavation in hyperbaric condition and ore transportation to the sea surface. In literature, different methods of excavation and rising techniques have been introduced. For the excavation part, [11] has designed a vertical mining approach using a trench cutter and a hydraulic grabber has been designed by [12]. In addition to the ongoing research activities, a few companies have been working on this concept. Neptune Minerals is one of them that has designed a set of mining equipment including a grabber, an SMS crusher and a mining tool to extract the SMS minerals offshore New Zealand [13]. The airlift system is proposed by Neptune Minerals for vertical transportation [13].

Nautilus Minerals is the most well-known company which is going to start large-scale mining in 2018 as a pioneer company [16]. Their first project is Solwara 1 located in the Bismarck Sea, 30 km offshore Papua New Guinea in 1600m water depth. The nominal production rate of Solwara 1 is set to be 1.8Million tons/year (dry equivalent)[17]. In this paper, the same DSM process, equipment and production rate as the Nautilus Minerals proposal are assumed.

The subsea mining equipment are three separate mining crawlers to drill, cut and collect the minerals called Auxiliary Miner (AM), Bulk Miner (BM) and Collecting Machine (CM), respectively. They are electrically fed and are controlled remotely by operators on the topside vessel. Their weight and physical dimensions are listed in table 1.

Since the SMS mounds are produced by volcanic activities, the area is usually rocky and rough. It is necessary to make the mining site accessible for the other crawlers by creating benches, which is done by AM. It has a cutter head installed on a long and powerful arm. After drilling, an installed pump-set on the AM will gather the ores with proper size (up to 5 cm in diameter [17]) and transfer them to a stockpiling device (hood) located on the seafloor via an S-shape tube [18].

BM has a heavy and large cutting head to crush the ores. There is a pump-set installed on BM, similar to AM, to transfer crushed ores to the stockpiling hood. CM suctions the crushed ores with its centrifugal pumps from the stockpiling hood and then transfers them to a subsea pump station via an s-shaped flexible tube.

The riser and lift system consists of a subsea pump station,

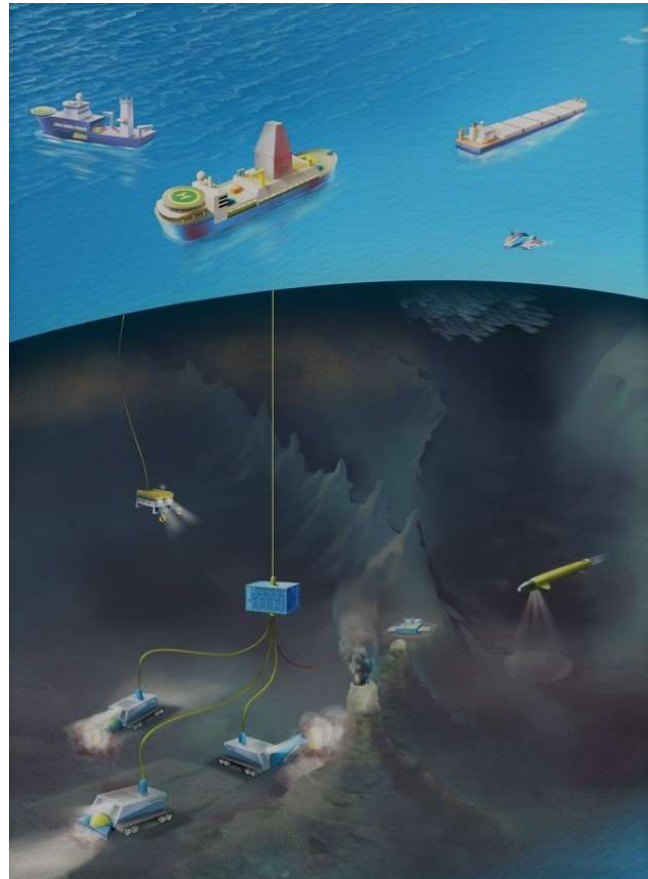


Figure 2 SMS mining process [14]

	Component	Dimensions [m]			Weight [ton] (Dry)
		Length	Width	Height	
1	AM	15.8	6	7.6	240
2	BM	14.2	4.2	6.8	280
3	CM	16.5	6	7.6	180
4	SSLP	6.4	5.2	3.7	129

Table 1: Size and weight of subsea mining equipment for Solwara 1 [15, 16]

called Subsea Lift Pump (SSLP), which is a set of diaphragm style positive displacement pumps. SSLP is suspended about 50m above the seafloor from a rigid steel riser. The size and weight of SSLP are also given in Table 1.

The main hub for DSM, proposed for Solwara projects, is an advanced mining vessel called Production Support Vessel (PSV), which is equipped with dynamic positioning (DPS 2 [19]) system. There is a dewatering plant on PSV, which extracts the ores excess moisture in order to preserve them from oxidation and prepare them for final transportation to shore. The excess water extracted from the minerals will be mixed with seawater via the triplex mud pumps (SSLP feeder) and sent back to drive the SSLP hydraulically.

Finally, the ores will be stored shortly on the PSV until they will be conveyed to a barge that transports them to shore for metallurgical process.

In addition to the electric loads mentioned above, there are also two smaller tethered ROVs. At least one of them is in continuous operation for mapping, biological and geological sampling and taking pictures and videos meanwhile. There

might be Autonomous Underwater Vehicles (AUV) diving around the mining site, while their installed onboard batteries provide the required power [20].

The focus of this paper is on the subsea mining equipment that is considered as the subsea electrical loads for the distribution system on PSV.

III. SUBSEA POWER DEMAND ESTIMATION

The aim of this section is to study major subsea power consumers including AM, BM, CM and SSLP, based on the data derived from Nautilus Minerals [16, 17]. The exploring ROVs have been neglected due to their low power consumption level (maximum 300 HP [21]) compared to all the other equipment.

However, the power needed for excavation and ore vertical transportation will increase for DSM in NMAR due to higher water depth. Table 2 contains a preliminary estimation of the required amount of power to run various loads on the mining equipment, considering that the Nautilus Minerals project was designed for 2500 m water depth, while the design depth for the NMAR is 3500 m.

The nominal power for crushing process of AM and BM cutter heads is 600 kW and 900 kW, respectively, for Solwara 1 [17]. By approximation, the relative power consumption for 350 bar has been estimated to be 30% higher than at 250 bar [22].

In addition, AM, BM and CM are advanced machines capable of moving on the seafloor with a rather slow speed equal to 600m/h for short distances [17], while for large distances, onboard cranes will lift them. They are also able to crawl slopes up to 10°[17]. The wheels power demand has been estimated by taking into account the overall forces including gravity, buoyancy, drag and friction.

There are also other electrical loads on AM, BM and CM, including smaller motors to run the arms, Uninterruptable Power Supply (UPS) system and the loads corresponding to navigation, control and data acquisition, lighting and cameras that are here grouped under the name “auxiliary loads”. Due to lack of more specific information, these loads have been represented as a single passive (aggregated) load in the configuration figures.

The SSLP can be driven directly by subsea electric motors or indirectly by hydraulic fluid (high-pressure seawater) injection. In Solwara 1 project, SSLP is fed hydraulically by eight (six of them are in continuous operation and two are spares) standard offshore triplex positive displacement mud pumps (1600HP each) installed on the vessel [17].

However, the required amount of power to lift the minerals in 2500m water depth (with the same production rate) is less than 6MW [13]. Therefore, it can be concluded that approximately 1MW (14%) will be lost in the system especially by mechanical friction in the hydraulic feeding tubes to SSLP.

Nevertheless, it is still worth investigating the effect of having the electrically fed subsea pump in the power system configuration due to its higher efficiency. In the future cases

		Cutter Heads	Pumps	Wheels	Auxiliary Loads	Installed Power	Max. Contemporary Power Demand
1	AM	0.8	0.5	0.7	0.5	2.5	1.5 (60%)
2	BM	1.2	0.5	0.8	0.5	3	1.9 (63%)
3	CM	-	1.2	0.6	0.5	2.3	1.4 (61%)
4	Electrically fed SSLP	-	8.4	-	-	8.4	8.4 (100%)

Table 2: The power consumption estimation [MW] for DSM in the Norwegian Sea (design depth: 3500 m)

like mining projects in NMAR, the pump system may be designed differently to match the new conditions such as higher water depth and harsh weather in the Norwegian Sea.

According to [13], there is a linear relationship between the riser pump required power and the water depth and this is the reason of having 8.4MW rated power for the power-fed pump motors in Table 2.

It should be noted that the load profile of the mining machines is assumed to be approximately 60% of the total installed loads in continuous operation for the worst case scenario, considering the non-simultaneity of the various loads’ operation. For example, the maximum loading of AM and BM occurs when they are in stand still position, cutter heads and pump motors are fully loaded and half of auxiliary loads are in operation at the same time.

The total installed power for subsea mining equipment is 16.3MW, including the power fed SSLP, and 7.9MW with hydraulically fed SSLP. Meanwhile, the maximum contemporary power demand is assumed 13.2MW (having the power fed SSLP) and 4.8MW excluding the SSLP as a subsea load. Since the auxiliary loads contribution in the maximum contemporary power demand is less than 15%, they have been neglected in the simulations presented later. Therefore, the total maximum power demand is 12.6 MW.

IV. POWER SYSTEM COMPONENTS AND CONFIGURATIONS

As mentioned in the previous section, PSV should provide the required amount of power to the subsea mining loads (13.2MW including SSLP or 4.8MW excluding SSLP). According to [23-25], 6 kV and 6.6 kV can be used for medium voltage subsea distribution system with power demand between 4 and 20 MW. In this paper, 6 kV and ± 3 kV have been chosen for AC and DC configurations, respectively. 3 kV has been selected for the voltage rating of all the induction motors used in the seafloor mining equipment [26]. Four AMA500L4L non sparking induction motors have been used to run SSLP unit [26]. The power and voltage ratings are 2240 kW and 3kV.

The operation of mining machines is controlled and monitored continuously by the operators on PSV. The reason of having full-control on the cutting process is to provide the

exact amount of power to the rock based on their physical properties by changing the cutter heads motor speed (torque). Otherwise, the rocks may turn into fine particles or plumes [27] during crushing or they may remain unaffected (no crack occurs). Consequently, Variable Speed Drive (VSD) will be a necessity for both AM and BM cutter head motors. Moreover, having VSDs to control the wheels speed seems reasonable.

Furthermore, all the pumps in the system should be driven by VSDs due to clogging prevention in the slurry transferring tubes and generating constant flow rate of density varying slurry.

In this section, two AC (50 Hz) and two DC distribution systems will be presented (Figures 3-7). PowerFactory /DIgSILENT software has been used to run power flow simulations to find the main comparing parameters such as power losses, voltage drop and reactive power generation (or consumption) in the system (Tables 3 and 4).

As cables play an important role in the power distribution

Number of Figure	Min. number of cables	Subsea converters*	Topside converters*	Subsea transformers	Topside transformers	Voltage level [kV]	Max voltage drop %	P-loss in cables[kW]	Required Q for cables & transformers [kVAr]
Including Riser Pump- max. contemporary power demand is 12.6 MW									
3	15	0	24	0	0	3 ac	12	1340 (11%)	1010
3	15	0	24	0	0	6 ac	7	930 (7.5%)	280
4	4	24	0	0	0	6 ac	5	440 (3.5%)	340
5	1	24	0	1	1	13 ac	2	140 (1%)	1100
6	5	12	0	0	0	±3 dc	5	470 (4%)	0
6	4	12	0	0	0	±6 dc	3	420 (3%)	0
7	2	12	1	0	1	±6 dc	3	150 (1%)	310
7	1	14	1	1	1	±9 dc	1	60 (0.1%)	450
Excluding Riser Pump- max. contemporary power demand is 4.2 MW									
3	8	0	16	0	0	3 ac	12	610 (15%)	240
3	8	0	16	0	0	6 ac	6	400 (9.5%)	80
4	3	16	0	0	0	6 ac	5	280 (7%)	60
6	3	8	0	0	0	±3 dc	4	250 (6%)	0
6	3	8	0	0	0	±6 dc	3	110 (3%)	0

Table 3 Comparison table of simulation results (including electrically driven riser pump and excluding Aux. loads); number of components, voltage level, voltage drop at the end of cable, power loss (P-loss) in the cable and reactive power demand (Q) for cables and transformers. (*converters are AC/DC, e.g. an AC/AC converter is considered as two converters), the white rows and the blue rows correspond to having AC or DC distribution on ship, respectively.

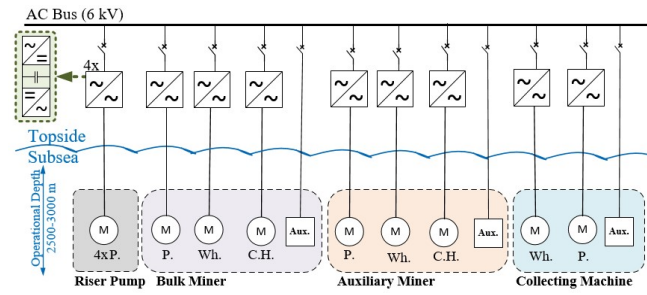


Figure 3 Individually AC , P. stands for pump, Wh. Stands for wheel, C.H. stands for cutter head and Aux. stands for auxiliary loads

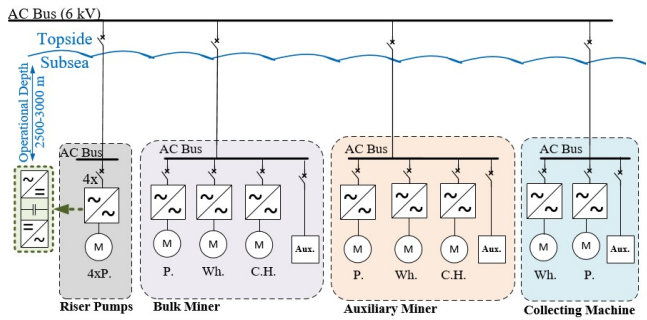


Figure 4 Separate AC-bus and subsea converters installed on the mining equipment, P. stands for pump, Wh. Stands for wheel, C.H. stands for cutter head and Aux. stands for auxiliary loads

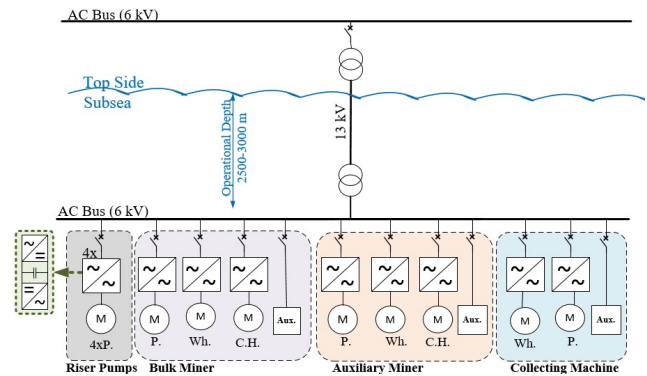


Figure 5 Centralized common AC-bus (High voltage AC distribution), P. stands for pump, Wh. Stands for wheel, C.H. stands for cutter head and Aux. stands for auxiliary loads

performance and efficiency. In this paper, three-core copper cables for AC and single-core copper cables for DC have been chosen. The cable length is set to 3.5 km and their loading is between 60% and 70 % during maximum contemporary power demand. The cable insulation rated voltage is set to be double the operating voltage. The number of cables is taking into account maximum current capability of commercially available cables [28, 29].

Simple P-Q loads with a typical power factor (cosφ) value equal to 0.85 have been simulated as the motors loads. The converters and transformers loss has been neglected in the simulations.

A. AC Distribution (50Hz)

As the subsea loads are mostly AC motors and AC distributions predominantly exist on ships, it makes sense to analyze AC distribution first. This is also in analogy to the oil and gas industry, where AC systems are popular and have been used for many years. As the distance between PSV and the loads is considered relatively short, it may be reasonable to install converters (operating under atmospheric conditions) on the vessel and feed the loads by subsea cables individually (Figure 3). Although its simplicity is an advantage, excessive level of voltage drop (12%) in the cables and high power losses (more than 10%) will make this solution unreasonable for both cases of riser pump included and excluded. If the voltage rating of the motors increases to 6kV, the voltage drop and power loss will improve to some extent but they will still remain very high. In addition, the weight and cost of 15 armoured subsea cables, and complexity in handling them are serious drawbacks of such configuration. Bundling the cables should be done to avoid their entanglement, while it will reduce the cables current capability due to proximity effect (which is neglected in the simulations).

It should be noted that in this paper, the number of motor loads have been reduced for the sake of simplicity (for example one for each cutter head and one for the wheel system), while even more subsea cables will be needed in reality.

The next AC possible configuration is to install subsea frequency converters (in pressurized chambers) on each mining machine and/or the riser pump (Figure 4) and create subsea AC buses (6 kV). The number of subsea cables will be thus reduced to three (excluding the riser pump), which is an advantage. If this configuration is compared to the similar 6 kV individually fed configuration explained earlier, the power loss will be reduced 50% and voltage drop will be improved as well.

In addition, the starting process of the motor loads will be easier and their speed can be controlled more precisely. Moreover, by installing the power converters on the equipment, the limited space on the mining vessel will be saved for ore and fuel storage. Since the mining location is more than 500 km away from Norway's coast and 350 km to the nearest island (Figure 1), fuel and ore transportation costs should be minimized by allocating as large space as possible for them on the vessel.

Furthermore, AM and BM should be heavy enough to damp the bouncing effect when they are transferring energy to the rocks and installing the power converters on them might be an advantage from that point of view.

However, subsea converters capable of operating under hyperbaric conditions up to 300-bar pressure [30-32] are very expensive. Another challenge of having subsea power converters is their difficult accessibility, which makes repair and maintenance complicated and costly.

The third considered AC solution is making a centralized subsea power hub at the seafloor with transformer and converters fed by one three-core or three single core high voltage power cable (Figure 5). This configuration is suitable for high power demand i.e. feeding the riser pump directly by electric power. By choosing 13 kV as the distribution voltage,

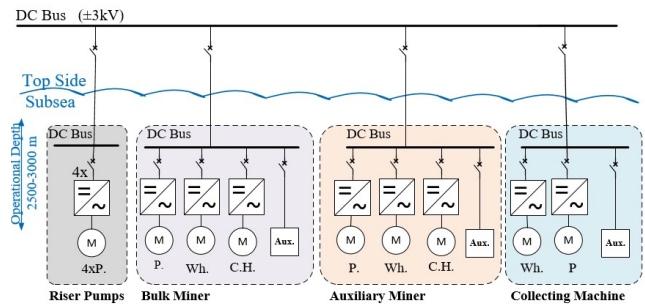


Figure 6 Separate DC-bus and subsea converters installed on the mining equipment, P. stands for pump, Wh. Stands for wheel, C.H. stands for cutter head and Aux. stands for auxiliary loads

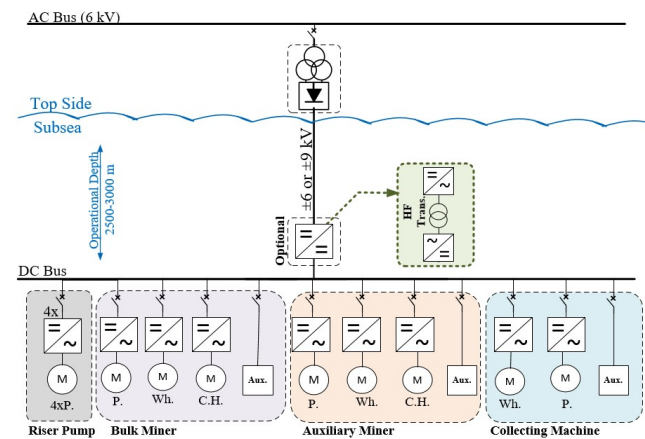


Figure 7 Centralized common DC-bus (High voltage DC distribution), P. stands for pump, Wh. Stands for wheel, C.H. stands for cutter head and Aux. stands for auxiliary loads

the voltage drop will be 2%, the power loss in the cable will be as low as 1%, but the reactive power exchanges due to cables and transformers will be relatively high equal to 1100 kVar. Moreover, high cost and space of the topside and especially subsea transformers should be taken into account as drawbacks.

B. DC Distribution

DC distribution on ship has been getting extensive attraction in recent years and it might be the best solution for future ship industry [33, 34]. This is a good motivation to consider DC distribution for the DSM project. Figure 6 shows a combination of DC distribution on ship and subsea DC distribution.

It is recommended to have a bi-pole system [35] and in order to have a rational comparison between AC (6kV) and DC systems, and considering the rating of available components on the market, both ± 3 kV and ± 6 kV have been simulated [35].

Although the voltage drop and the cable power loss is almost similar to the 6 kV-AC configuration shown in Figure 4, DC cables are more efficient than AC ones with the same voltage (± 3 kV and 6 kV) and current ratings, because there is no need for reactive power consumption or generation. Moreover, the insulation design of a cable is done considering the peak value of the voltage, which is 3 kV for the ± 3 kV-DC system and 4.9 kV (peak value of the phase voltage) for the 6 kV-AC

distribution. Consequently, the cost, size and weight of the insulation will be reduced in DC distributions.

The other advantage of having DC distribution is having less number of components, which improves the system overall efficiency, weight, cost and reliability. The converters used in the DC configuration are only DC/AC inverters, while a combination of AC/DC and DC/AC converters is necessary for similar AC configuration. In addition, the DC/AC converters operate bi-directionally that enables the use of regenerative braking energy.

However, a penalty of the configuration shown in Figure 6 is the lack of galvanic isolation, which plays an important role in fault detection and loads protection during faults in the system. Moreover, extinguishing short circuit currents in DC systems is still a technological challenge [36].

There is another possibility of feeding the subsea loads by having a centralized DC bus fed from one high voltage DC cable, as demonstrated in Figure 7. It is sensible to have this configuration when power demand is high; i.e. when the riser pump is included in the subsea loads. Both ± 6 kV and ± 9 kV have been simulated and the cable power losses are the least compared to the other topologies. In addition, number of cables has been reduced. However, it seems necessary to have a subsea DC/DC converter with high power rating to provide both voltage reduction and galvanic isolation. In addition to its high cost, careful considerations should be taken into account for its design.

AC and DC distributions on ship can both feed a centralized common DC bus on the seafloor. The only difference is the topside components, which is a transformer rectification unit for the ship AC distribution and probably a DC-DC boost converter for the DC alternative.

It is worth mentioning that in the DC distribution, the motor loads reactive power demand is supplied by the subsea converters, while in the AC topologies, it is supplied by the topside AC bus.

C. Non-Standard Frequencies

High Frequency AC (HFAC) [37-39] and Low Frequency AC (LFAC) [40] are the other options used in both industry and research studies for subsea applications.

In HFAC distribution (illustrated in Figure 8), 400 Hz AC voltage will be used while the voltage level should be high

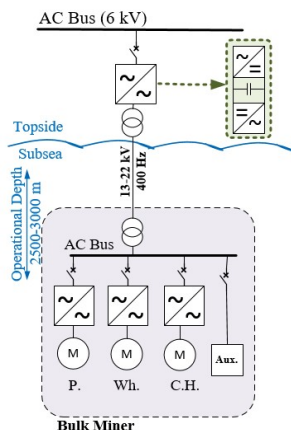


Figure 8 High Voltage-High Frequency AC (HVHF) for one sample mining machine, P. stands for pump, Wh. stands for wheel, C.H. stands for cutter head and Aux. stands for auxiliary loads

enough to compensate the increased reactive power associated to of the cables. Therefore, two high frequency transformers should be installed for each mining machine in addition to an AC/AC or DC/AC configuration for ships with AC and DC distributions, respectively. Therefore, the number of involved components will make this solution irrational.

On the other hand, LFAC (16.66 Hz) alternative is suitable for very long step-out motor drives. However, it is not recommended for DSM due to very large topside and subsea transformers and additional topside converters.

V. CONCLUSIONS

DSM definitely belongs to the near-future industry, but the number of studies related to the most efficient and economically viable power system design of DSM projects is still very limited. This paper compares different AC and DC alternatives, in order to orient the decision on the electrical system architecture from the very first stage of any DSM project, since this can have a significant impact on the operation and performance of the entire installation over the project lifetime.

Based on the discussions, configurations with topside converters are not recommended due to high number of loads installed on the mining machines, which leads to numerous subsea cables. In addition, high power demand required for DSM will result in high voltage drop and power loss in such configurations. In addition, high frequency and low frequency distributions are not suitable for this application.

Having AC or DC buses on the mining equipment, preferably with voltages higher than 6 kV, seems to be practical, since their power loss and voltage drop are in acceptable ranges. However, the number of power electronic converters may be in the favor of the DC alternatives that have no rectifiers.

DSM in future will go to deeper oceanic areas. Therefore, the power required to run such projects would be higher, which makes the centralized AC or DC solutions more reasonable. In these configurations, the ship space is unoccupied by the power equipment feeding subsea components. In addition, harvesting the geothermal energy from the hydrothermal vents may be fulfilled in future to increase the contribution of renewable energies. Consequently, the related devices can be integrated with the subsea centralized power hub.

In general, operational cost of DSM projects is very high. Therefore, it is necessary to design an advanced, efficient (loss minimization) and reliable power distribution system. Since repair and maintenance is very difficult and costly, the number of power components should be minimized, while considering redundant solutions. In addition, subsea cables weight and numbers should be minimized to reduce their gravity forces on the mining vessel. Taking into account all the above factors, it can be concluded that the DC distribution can be an appropriate alternative, provided that a suitable technological maturity of MVDC circuit breakers and isolators will be reached.

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