Cable Selection Considerations for Subsea Vehicles

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***Abstract* — The aim of this paper is to present a methodology for selecting proper voltage level and power cables as a part of the AC distribution system design for subsea vehicles, such as Remotely Operated Vehicles, seafloor trenchers and subsea mining machines. The design methodology encompasses a wide range of cable lengths and load power demands (up to 7 MW). Furthermore, both electrical and mechanical considerations have been taken into account in order to provide an optimum design for the power cable. The final decision is made considering the main parameters including voltage drop, power loss, reactive power exchanged in the cable, conductor cost, and top and bottom tension forces acting on the cable.**

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

I. INTRODUCTION

Today subsea vehicles are employed to discover and exploit the ocean energy, oil, gas and mineral recourses. These unmanned vehicles, controlled autonomously or remotely, make the deep areas accessible for humans. Autonomous Underwater Vehicles (AUV) are oceanographic tools to map and collect various data from the depths and Remotely Operated Vehicles (ROV) are made for different purposes including taking videos, gathering data and sampling, small-scale drilling, repairing and maintenance of offshore and subsea structures [1, 2]. AUVs and ROVs are mobile buoyant vehicles, and propellers are needed to control their positioning. There are also heavy seafloor vehicles for trenching the seabed and burying the cables called trenchers, ploughs and cable burial tractors, respectively. Recently, deep-sea mining vehicles such as Manganese Nodules (MN) collectors and Seafloor Massive Sulfides (SMS) mining machines have joined the subsea vehicles category. MN collectors are designed to suction the scattered polymetallic nodules, which are transported to the surface via a subsea pump (and possibly a crusher) [3]. MNs usually exist in 4-6 km water depth. Moreover, SMS mining vehicles drill the hill-shaped volcanic areas, which usually exist at depth between 1.5 and 4 km, to make smaller pieces of minerals by cutting and crushing them. The minerals can be transported to the supporting vessel by integrated pumps on the vehicles or by separate pump modules [4, 5].

AUVs power requirement is the lowest among the aforementioned subsea vehicles (typically 0.2-2 kW) [6]; therefore, onboard rechargeable batteries can provide sufficient power for their needs. Except from them, all the other subsea vehicles are fed from topside generators installed on a vessel or platform via a fatigue-resistant dynamic power cable or umbilical. It is worth mentioning that the term umbilical mostly refers to the power cables that are capable of transferring hydraulic fluids in addition to power and communication signals, which is the case for most of today's hydraulic subsea vehicles. However, the technological tendency is toward all-electric vehicles in future [7], due to their better performance in ultra-deep waters, compactness (lower weight and volume), lower maintenance cost, higher reliability and efficiency [8]. Therefore, the focus of this paper is only on the power cables without fluid transfer capability.

This work was supported by the Oceans Pilot project on Deep-Sea Mining at NTNU.

The power consumption levels of the subsea vehicles vary depending on the applications and depth of operation. For ROVs, the installed power is typically between 50 and 300 kW. Trenchers and cable burial tractors usually require 200-2400 kW of electric power. The installed power of SMS mining vehicles is typically 1-3 MW [9]. However, MN collectors require less power than SMS mining vehicles due to the absence of drilling activities although they operate in deeper waters [10].

This paper is investigating three-core dynamic power cables for subsea vehicles operating in deep waters with lower power (<7 MW) and voltage (<11 kV) requirements from both electrical and mechanical perspectives. The main contribution of this paper is presenting a methodology for selecting a suitable AC voltage level and three-core power cables feeding the subsea vehicles as a part of their power distribution system design procedure. In section II, the electrical properties that play important roles in cable selection procedure will be introduced and in section III, the important mechanical factors will be discussed. The proposed methodology for selecting the proper cable will be explained in section IV by presenting three examples.

II. ELECTRICAL POWER CONSIDERATIONS

The first stage in the design procedure is gathering the primary inputs such as the vehicle missions, number of major loads and the total maximum contemporary power

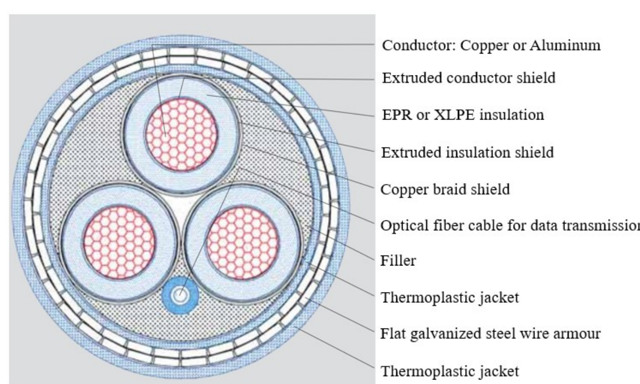

Fig. 1. Cross-section of a typical three-core subsea power cable with double layer armoring [11].

demand, in addition to the voltage level of the main surface electric network to which the vehicle is going to be connected. Moreover, the maximum depth of operation and data related to the weather and water conditions, such as wave height, current, wind speed and water temperature, at the operating site should be collected.

Generally, multicore cables (three-core for AC power systems) are used for subsea applications due to their compactness and minimizing the number of connectors. They contain various parts as depicted in Fig. 1:

- Conductors for power transfer that can be made of copper or aluminum.
- Insulation to build an effective barrier between the conductors with potential difference and prevent electric arc. Cross-linked polyethylene (XLPE) and ethylene-propylene rubber (EPR) are common insulations for dynamic submarine cables [12]. It is necessary to prevent moisture ingress into the XLPE insulation by applying lead alloy sheath around them.
- Semiconducting screen that is grounded and keeps the electric field in the cable homogenous and with a radial pattern to reduce the leakage currents and prevent insulation breakdown.
- Water-blocking and corrosion resistant sheaths around the insulation and armoring of the cable to prevent water ingress and corrosion.
- Optical fibers to allow signal transmission between the vehicle and the topside vessel, and provide a communication path for measurement and command signals. They are also used for detecting the fault location in the cable.
- Armoring to increase the mechanical strength and provide tension stability of the cable. It is recommended to have galvanized round steel double helix armoring wrapped in opposite directions on the dynamic cable in water depth greater than 500 m [13]. It reduces high tension elongations of the cable by counterbalancing or even canceling the torsional forces and reaching a torque balance, especially for

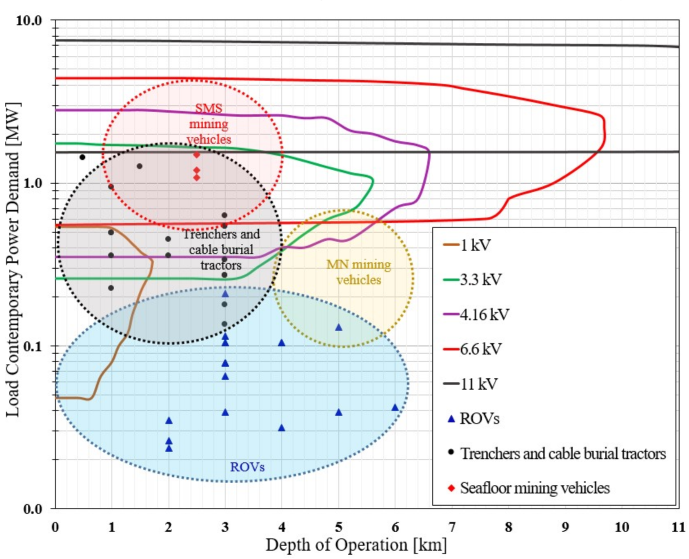

Fig. 2. The boundaries of different standard medium voltage levels considering subsea vehicles aggregated power demand and depth of operation. The surveyed ROVs, trenchers, cable burial tractors and SMS mining machines are illustrated as dots.

buoyant vehicles operating in deep waters [12-14]. Therefore, it not only provides better mechanical protection, but also the cable tendency to rotate is reduced. The tether cable armoring is usually made of bulky synthetic fibers such as Kevlar to make the cable lighter and naturally buoyant [15].

A suitable voltage level and corresponding power cable should be selected in order not to exceed the temperature limit and the voltage drop requirements along the cable. The type of distribution voltage can be selected between Alternating Current (AC) and Direct Current (DC). In this paper, only AC will be discussed. A proper voltage level based on the recommended voltage levels stated in relevant standards should then be defined [16]. Typical voltage levels for the ROV umbilicals are 1, 3.3, 4.5 and 6.6 kV [17]. In this paper, AC (50 Hz) medium voltage range 1-11 kV will be covered for subsea vehicles with power demand between 50 kW and 7 MW.

The boundaries of applicable standard voltage levels (stated in [16]) can be defined by performing load flow analyses, varying cable length and power consumption level, as shown in Fig. 2. Submarine three-core Copper (Cu) cables with conductor cross sections 10-240 mm^2 for 1 kV, 25-240 mm^2 for 3.3 kV, 25-400 mm^2 for 6.6 kV and 70-400 mm^2 for 11 kV [18] have been considered to fulfill two criteria:

a) Maximum voltage drop at the load terminal is within 10%. Since the line length is less than 5 km, it is considered as a short line and the problems related to the distant locations will not be present in this case. However, the voltage drop can be still high (more than 10%) since having the cable with minimum diameter is an advantage to reduce the mechanical forces acting on the cable.

b) Cable loading is between 50% and 80%.

This criterion depends on the temperature consideration of the cable and probable future expansion of the power loads. If the cable is wounded on a drum, the maximum number of cable layers on the drum and its cooling method define the maximum allowed current [19]; otherwise, the cooling process in the water is very effective and the cable can be 100% loaded.

The y-axis of Fig. 2 represents the contemporary power demand corresponded to a 70% load factor. In addition, the cable length is assumed to be 20% more than the operational depth.

The information presented in Fig. 2 is helpful in the basic steps of the design procedure in order to identify possible voltage levels given the information about power consumption and maximum depth of operation.

Furthermore, a survey on: 1) work-class ROVs (with total installed power from 50 HP to 400 HP), and 2) trenchers and cable burial tractors (with total installed power up to 3200 HP) has been done. They have been depicted in Fig. 2 as blue triangles and black circles, respectively. In addition, Fig. 2 included also three SMS mining vehicles (red squares) designed for 2500 m water depth with the total installed power from 1.8 to 2.5 MW. Their installed power and depth of operation have been included in the Appendix (Table V)

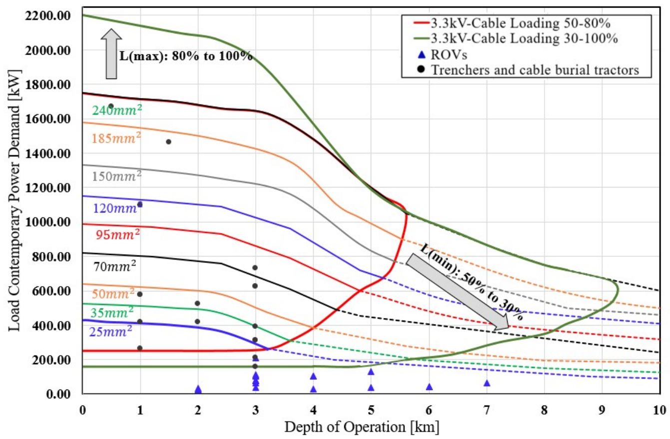

Fig. 3. Sensitivity analysis on the cable-loading criterion. The cables involved in defining the boundary have been specified for the 3.3 kV case.

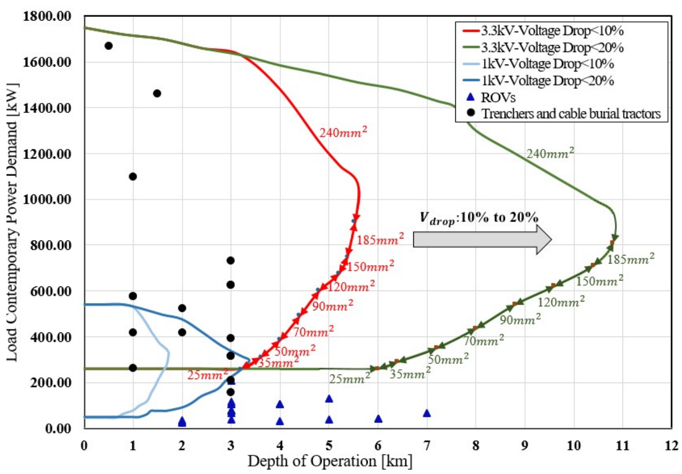

Fig. 4. Sensitivity analysis on the voltage drop criterion. The cables involved in defining the boundary have been specified for the 3.3 kV case. The same pattern could be seen for the 1 kV cable.

as well. This survey is beneficial in assessing the state-of-the-art technology used in such vehicles.

For a customized design, the user can change the loading and voltage drop limits in order to modify the boundaries in Fig. 2. The result of the sensitivity analysis performed on the cable loading and voltage drop limits have been illustrated in Fig. 3 and Fig. 4, respectively. The information about the cable cross-sections used in each region has been given as well. Increasing the cable upper loading from 80% to 100% makes the upper part of Fig. 3 stretched, while lowering the minimum allowed cable loading to 30% will cover larger water depths. As an example, assuming that the vehicle's operational depth is 2 km and its maximum contemporary power demand is 1 MW and 3.3 kV is selected as the distribution voltage. If 120 mm^2 cable is selected, the cable loading will be less than 80 % (71 %), but if 95 mm^2 cable is selected, it will be loaded more than 80% (83%). It might be also possible to use 70 mm^2 cable that will be approximately 100% loaded.

Increasing the allowed maximum voltage drop from 10% to 20% stretches the boundaries to the right hand side meaning that power can be transferred to longer distances, according to intuition (Fig. 4).

The surveyed ROVs concentrate on the right-hand side of the 1 kV boundary. The reasons can be either accepting more than 20% voltage drop at the cable terminal in the case of 1 kV distribution voltage, or using smaller cross section than 25 mm^2 if their distribution voltage is 3.3 kV. Most of the surveyed trenchers and cable burial tractors are in the 3.3 kV boundary. However, they may have higher distribution voltage levels such as 4.16 or 6.6 kV (Fig. 2).

III. Mechanical Considerations

Mechanical considerations are of great importance when selecting dynamic cable configurations for mobile subsea vehicles. Internal (stiffness, inertia) and external (environment) forces are important factors that affect the design criteria. To analyze the mechanical properties two key parameters are investigated: Top and bottom tensions. It is important to reduce the top and bottom tension forces acting on the cable terminals. As the maximum tension will occur at the top end of a negative buoyant cable, it is the point of largest concern when it comes to mechanical limitations (Max tension, snap loads). The bottom tension should also be minimized since it affects the maneuverability and functionality of the subsea vehicle (especially the buoyant ROVs). The cable weight and diameter have a very high priority in the cable design procedure for ROV applications.

To calculate the tension forces for different scenarios the cables are modeled as beams represented by the Euler-Bernoulli beam equations [20]. The beam equations are solved using the linear finite element approach. Based on the static deflection of the cable, both top and bottom tensions of the cable are found directly from the stiffness forces:

$$K_g u = F_s \tag{1}$$

where K_g is the global stiffness matrix, u is the cable deflection and F_s is the stiffness force.

In the analysis waves are not considered as the wave forces will only affect a small portion of the cable. However, wave forces will have a large impact on the top tension since the surface vessel or buoy is highly affected by the incoming waves. It is therefore assumed that the cable is supported by a heave compensated system or a tieback below the wave-affected zone and the wave forces can therefore be neglected.

To perform the analysis, a couple of key parameters must be determined: the current and cable stiffness. The depth varying current forces, which contribute to the environmental drag, are chosen from the Mohn's ridge at the mid-Atlantic ridge. It is an area with large amounts of mineral resources and is thought of as a possible location for potential deep-sea SMS mining. The current velocities, illustrated in Fig. 5, are found from regional Ocean Modeling System (ROMS) database given in the Norwegian Meteorological Institute's database [21].

The structural stiffness for the cables must be calculated. Since the cables consist of multiple layers of different materials, it is not possible to calculate the axial and flexural rigidities directly. Therefore, an equivalent value for the axial and flexural rigidity is introduced. The equivalent

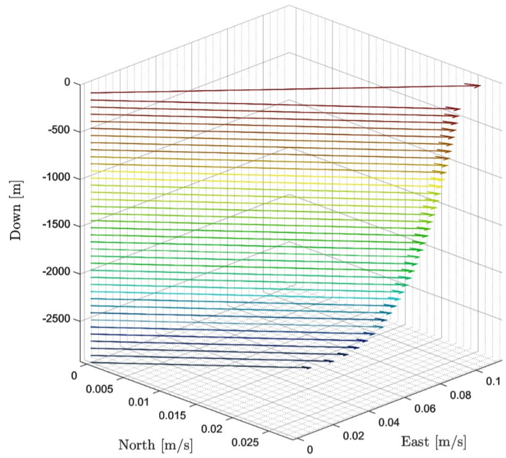

Fig. 5. Typical current velocity profile of the Mohn's ridge area.

rigidity is a superposition of the rigidities of the different cable layers. For an N-layered cable, the flexural and axial rigidities can therefore be written as:

$$EI_{eq} = \sum_{i=1}^{N} E_i I_i \tag{2}$$

$$EA_{eq} = \sum_{i=1}^{N} E_i A_i \tag{3}$$

where E is the Young's module [GPa], A is the cross-section area [m^2] and I is the 2nd moment of inertia [m^4]. This simplification of course neglects nonlinear contact force between different layers, but should serve as a reasonable approximation. It should be mentioned that in this paper a single layer steel armoring with 4 mm thickness has been used for the forces calculation, cables diameter and weight estimations, which is equivalent to double layer armoring of 2 mm thickness when using an equivalent cable stiffness (Equations 2 and 3).

There are two possible configurations to provide power, control and communications signals to the subsea vehicles: direct connection, as illustrated in Fig. 6(a), and connection through an intermediate structure, for instance Tether Management System (TMS) in work-class ROV applications, as shown in Fig. 6(b). The cable design considerations for these cases are different, especially from the mechanical perspective. Smaller ROVs such as micro-ROVs can be fed directly via a neutrally buoyant flying tether between the surface and the vehicle [22]. The use of the TMS significantly reduces the effect of the umbilical weight, drag and vertical movement on the ROV especially in deep areas. In fact, the water current drag forces will be mitigated by the heavy vertical power cable connecting the TMS to the vessel, and the ROV is fed by a few-hundred-meter neutrally buoyant tether connected to the TMS.

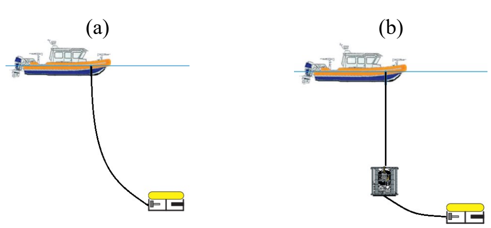

Fig. 6. Feeding subsea vehicles directly (a) and via TMS structure (b).

However, the TMS structure introduces more joints and connectors to the system, which are prone to mechanical and electrical failures. It is recommended to design the subsea distribution system with minimum number of joints and disconnectors to increase its lifetime [7].

The effect of using a TMS can be seen by performing a simple case study where a subsea vehicle (ROV/trencher) is given a prescribed path. The system used is a trencher-sized vehicle equipped with a three-core 3.3 kV cable with 50-mm^2 conductor cross-area for each core. The submerged weight of the cable is 28.56 N/m and the operating depth of the operation is 3000 m. The same current conditions as was used for the mechanical considerations are used. The TMS used in this study has a submerged weight of approximately 4500 kg.

The results for the cable forces during the maneuver is depicted in Fig. 8. Note that the cable forces on the vehicle when a TMS is used are not calculated, as they are assumed negligible. It can clearly be seen that significant cable forces are imposed to the vehicle without a TMS and it can even increases to more than 20 kN at 1100 s. However, using TMS will increase the top tension forces (which is around twice in this case study) and this increase can be simply explained by its weight. It is possible to reduce the top tension forces by adding buoyancy elements with positive buoyancy along the cable. Adding one element with a positive buoyancy force equal to half the cable weight on the middle of the cable will reduce the top tension by approximately 50%.

As the vehicle dynamics are not simulated, the vehicle is assumed to follow the path (shown in Fig. 7) perfectly. The simulations are therefore not a representation of a realistic maneuver, but works as a proof of concept to illustrate the huge difference between using a TMS and not.

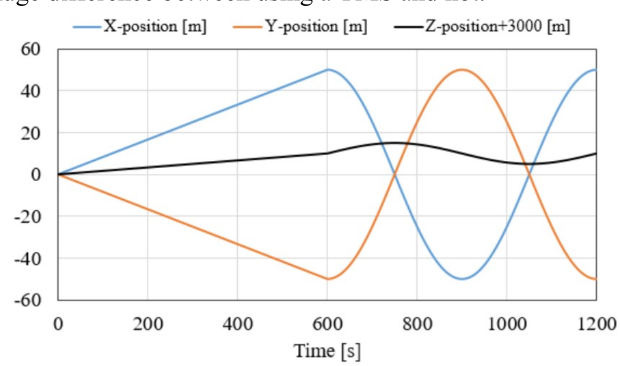

Fig. 7. The prescribed vehicle path used in the simulations.

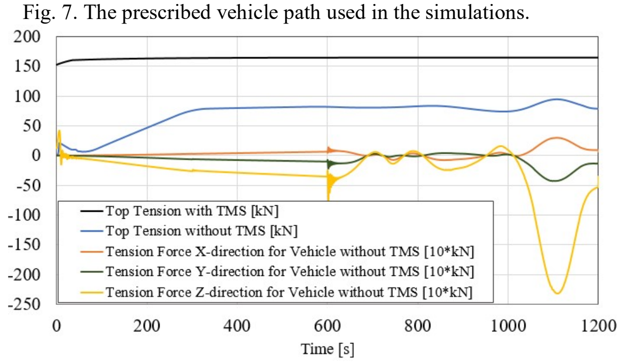

Fig. 8. Top and bottom tension forces in both with and without TMS cases.

IV. Cable Selection Methodology

The proposed cable selection technique is used for comparing various alternatives based on quantifying all the important parameters and scaling them in a fixed grade system between 0 and 10. In other words, all the values in the same category are normalized based on their maximum value and the highest grade (10) will be assigned to the maximum number. Finally, the normalized values are going to be illustrated in a radar diagram to qualitatively reveal the best alternative of which the corresponded area is the smallest among the compared choices. It should be noted that the user could also modify the grades by giving different priority weights to the various parameters based on the design priorities of each application.

In this paper, voltage drop (V_{drop}), power loss (P_{loss}), reactive power exchanged (Q_{ex}) in the cable and cable current loading (L), as the electrical parameters, top and bottom tension forces (F_{top} and F_{bottom}), as the mechanical parameters, have been considered as the basis for comparison among different alternatives. Moreover, the dry weight of the cable (W_{dry}) and its overall diameter (D) can also be important for the designers; hence, they are also included in the evaluation. The cable cost is sometimes the most important factor in the cable selection process; however, the cost data is not easily accessible since the subsea cables are usually custom made. However, in this paper the cable cost is replaced by the conductor cost that can be calculated easily by knowing the cables cross sections and material. The applicability of the proposed cable selection methodology will be better explained by giving some examples.

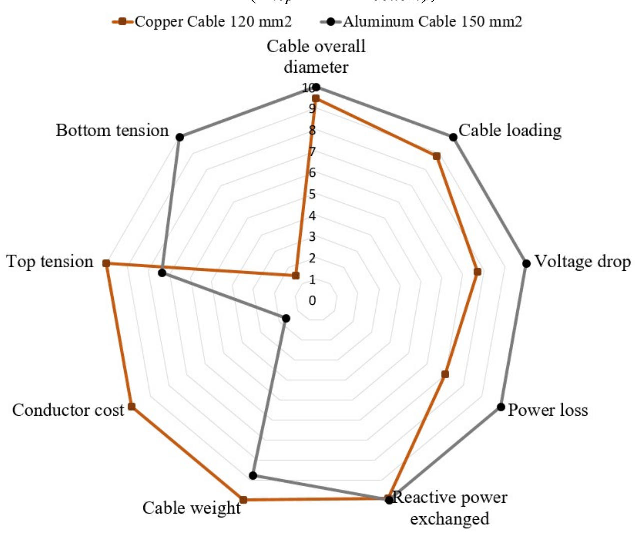

Fig. 9. Comparison between two conductor materials, Cu and Al, used in three-core 3.3 kV power cables feeding an 800 kW load operating in 4 km water depth. The enclosed areas are 194 and 221 for Cu and Al-cables, respectively.

Table I. The calculated values of the parameters corresponded to Fig. 9.

	V_{drop} [%]	P_{loss} [kW]	Q_{ex} [kVAr]	L [%]	F_{top} [kN]	F_{bottom} [N]	W_{dry} [tons]	D [mm]
Cu	7.4	66	28	62	192	172	32.2	60
Al	9.6	95	28	70	141	1138	28.1	65

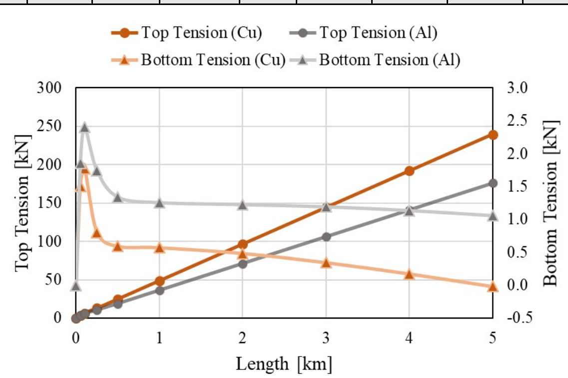

Fig. 10. Top and bottom tension forces of Al (150 mm^2) and Cu (120 mm^2) cables for various lengths between 0 and 5 km (the load power demand is 800 kW provided at 3.3 kV voltage level).

The first step in the cable design is selecting the cable material including the conductor. Copper (Cu) and aluminum (Al) are the popular metals used in cables. Cu is generally the most common conductor for the submarine cables [13] and it is usually the conductor used in the umbilicals due to its higher conductivity (1.7 times higher than Al); thereby the overall diameter of the cable will be reduced. In addition, Cu is more resistant against corrosion than Al in the case of water ingress. Furthermore, Cu conductors are more flexible, have a higher fatigue resistance and breaking strength than Al conductors. However, Cu is approximately 3 times more expensive than Al [23] and Cu-cables can be up to six times more expensive than Al-cables which makes them less attractive [24]. Another advantage of using Al is its lower density (3.3 times lower than Cu), which makes it lighter than Cu and can be beneficial in some of the applications, as tether cable. Usually one level larger cross-section of an Al-cable should be selected to have the same power transfer capability as a Cu-cable. Even in this case, Al-cable weight is still lower than the corresponded Cu one.

It is worth mentioning that if Al dynamic cables are used for subsea applications, special care should be taken to the mobile joint areas with high drag forces acting on them. It has been proposed to connect a short piece of an appropriate Cu-conductor between the electrode holder and the Al cable terminal in order to make it more flexible and increase its strength [13].

In Fig. 9, a three-core 120 mm^2 Cu-cable is compared with a three-core 150 mm^2 Al-cable to feed an 800 kW load (0.9 lagging power factor) operating in 4 km water depth. The 3.3 kV has been selected for the distribution voltage level. This load can be either a seafloor trencher or an SMS mining vehicle. The calculated values presented in Table I are normalized based on the maximum value and scaled between 0 and 10. The effect of conductor filling factor and diameter increase on the other part of the cable have been neglected.

The proportional conductor cost is estimated as:

$$C_{Cu} \approx \frac{A_{Cu} \times \rho_{Cu} \times C^0_{Cu}}{A_{Al} \times \rho_{Al} \times C^0_{Al}} C_{Al} = \frac{120 \times 8.96 \times 3.19}{150 \times 2.7 \times 1} C_{Al} = 8.5 C_{Al} \tag{4}$$

where A is the cross section area of the conductors [mm^2], ρ is their density [gr/cm^3] and C^0 is the metal cost [USD/lb] given in [23]. The overall cable cost difference between the

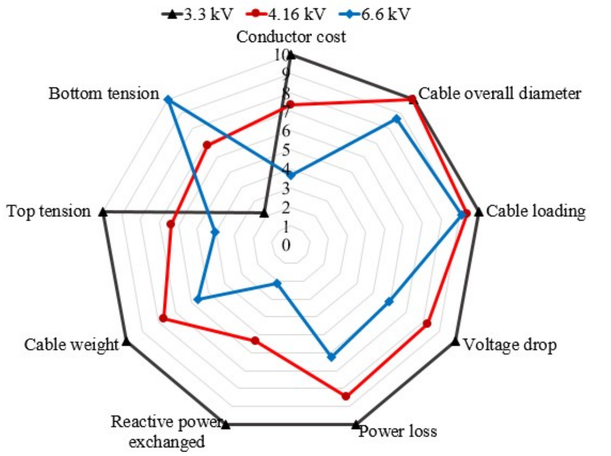

Fig. 11. Comparison between three distribution voltages feeding an 800 kW load operating in 4 km water depth. The conductor cross sections for the cables are 95 mm^2, 70 mm^2 and 35 mm^2 for 3.3, 4.16 and 6.6 kV, respectively. The areas enclosed by the three curves are 228, 180 and 143.

Table II. The calculated values of the parameters corresponded to Fig. 11.

Voltage [kV]	V_{drop} [%]	P_{loss} [kW]	Q_{ex} [kVAr]	L [%]	F_{top} [kN]	F_{bottom} [N]	W_{dry} [tons]	D [mm]
3.3	8.6	77	27.1	69	166	420	28	57.5
4.16	7.1	65	14.4	65	106	1300	21.6	57.4
6.6	5.1	48	5.8	63	67	1899	15.8	49.6

two alternatives is smaller in reality due the larger diameter of Al-cables.

According to Fig. 9, the voltage drop, power loss and cable loading are lower in the Cu-cable as expected, while approximately equal reactive power is exchanged in both of them. The Cu-cable overall diameter is 6% smaller than Al-cable overall diameter, while its weight is 15% larger. In contrast with the 36% larger top tension force acting on the Cu-cable, its bottom tension force is 82% smaller than Al-cable. It can be concluded that the Cu-cable is a better alternative since in the radar diagram, shown in Fig. 9, the area surrounded by its related parameters is 12% smaller than the corresponded Al-cable area. If the conductor cost is replaced by the cable total cost, their difference will increase, which makes the use of copper even more reasonable.

It is worth mentioning that if priority factors (weight coefficients) are going to be assigned to the most important parameters such as cost, the shapes of the radar diagram and the best alternative corresponding to the smallest area may change. This leaves the system designer the freedom to use the proposed methodology as a flexible tool.

Fig. 10 depicts the mechanical simulation results for the Al and Cu-cables used in Fig. 9 at various lengths. The top tension is approximately two orders of magnitude larger than the bottom tension forces as expected. Although the top tension is linearly increasing with the operational depth, the bottom tension is decreasing with smaller slope at the depths more than 1 km. The nonlinearity part of bottom tension is most likely a result of numerical errors. As the same number of elements are used for all simulations (N=50) the resolution for the shortest cables is much better than the longer cables. The bottom tension is however negligible.

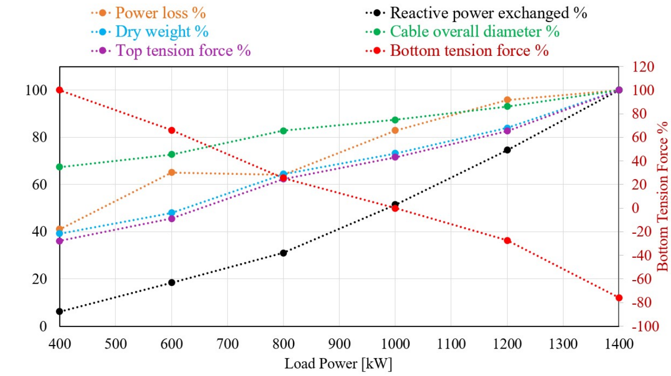

Fig. 12. The relation between design parameters and load power demand for operating in 4 km depth of operation. The distribution voltage is 3.3 kV. Bottom tension force has a different vertical axis (right).

Table III. The calculated values of the parameters corresponded to Fig. 12. Bottom tension force changes its direction when the cable diameter is more than 60 mm.

Load [kW]	$A_{Conductor}$ [mm^2]	P_{loss} [kW]	Q_{ex} [kVAr]	F_{top} [kN]	F_{bottom} [N]	W_{dry} [tons]	D [mm]
400	50	43	6	111	671	19.6	49.7
600	70	68	17	140	444	24	53.6
800	120	66	28	192	172	32.2	57.5
1000	150	86	46	220	0	36.6	60.2
1200	185	99	67	254	-183	42	68.6
1400	240	104	90	308	-509	50	73.7

Furthermore, the Cu-cable has larger top tension, while its bottom tension is smaller than Al-cable.

Since copper is traditionally more common for submarine applications, the other figures and tables that presented in this paper are based on the datasheet of copper cables.

Fig. 11 and the corresponding Table II give information about comparing three voltage levels for feeding an 800-kW subsea load in 4 km water depth. Except for the bottom tension force, all the other parameters reduce by increasing the voltage level.

The cable cost difference is less than the conductor cost difference, shown in Fig. 11, since the insulation thickness will increase by increasing the voltage. However, it may be necessary to install larger transformers as an additional cost. As the enclosed area of 6.6 kV distribution voltage is smaller than 4.16 and 3.3 kV, it results in a better alternative.

The variation of the design parameters by increasing load power demand from 400 kW to 1400 kW (200 kW steps) is illustrated in Fig. 12. The calculated parameters are listed in Table III. The maximum voltage drop is set to be 10% and the cable loading is between 50% and 80%, which requires different cable cross sections at each load-step. All the values of Fig. 12 have been normalized based on the maximum value of each parameter to simplify the comparison. The top tension force is increasing at the same rate of cable weight. In addition, the rate of increase in the cable reactive power exchanged is the highest among the parameters.

In the case of multi-machines operation such as SMS mining, there are two alternatives to feed the subsea vehicles: separate feeding with individual power cables or common feeding via one power cable and a subsea switchgear (power hub structure). Each of these configurations has advantages and disadvantages listed in [9]. However, when the number of vehicles and their total power consumption increases (typically above 5-10 MW), it is more reasonable to use the common power hub configuration to reduce the power system complexity, increase its efficiency and reduce number of joints and connectors [9].

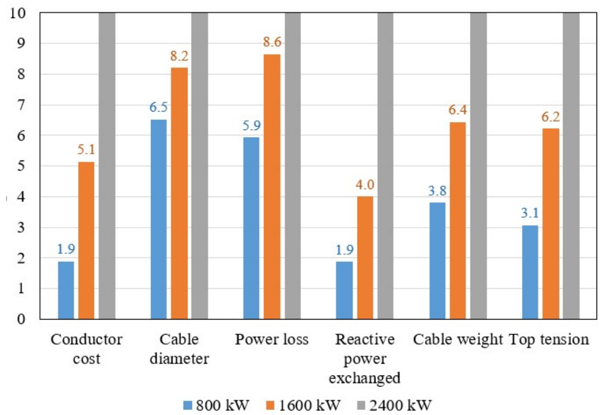

Fig. 13. Comparison between three different cables feeding 800, 1600 and 2400 kW contemporary loads with 6.6 kV distribution voltage. The operational water depth is 4 km. The conductor cross sections for the cables are 35 mm^2, 95 and 185 mm^2.

Table IV. The calculated values of the parameters corresponded to Fig. 13.

Load [kW]	V_{drop} [%]	P_{loss} [kW]	Q_{ex} [kVAr]	L [%]	F_{top} [kN]	F_{bottom} [N]	W_{dry} [tons]	D [mm]
800	5.1	48	5.8	63	67	1899	15.8	49.6
1600	4.1	70	14	66	137	1032	26.8	62.4
2400	3.6	80	35	62	221	753	41.7	76.0

Fig. 12-13 can be used as a comparison chart for multi-machines operations operating with 3.3 kV and 6.6 kV respectively. A specific comparison between three subsea loads (800 kW, 1600 kW and 2400 kW) operating in 4 km water depth is depicted in Fig. 13. The calculated design parameters are given in Table IV. This figure can be helpful to compare separate and common feeding of two or three vehicles. Assuming similar contemporary power demand for each of them equal to 800 kW (the total installed power is approximately 1.1 MW).

It can be concluded that having a common feeding for two or three vehicles with one power cable reduces power losses, total diameter of the cable (which is related to the storage space to be occupied on the ship) and total cable weight.

However, coiling of the cable will be more difficult if its diameter increases. In addition, the reactive power exchanged in the cable and the conductor cost will increase by having a common feeding instead of separate feeding. If the cost of the other part of the cable is also taken into account (by considering the diameter increase), it will be even more expensive to have one common cable. Furthermore, the top tension is twice and three times more for the 95 mm^2 and 185 mm ^{2} cables, respectively than for the 35 mm^2 one. Therefore, they should be able to withstand these forces during operation. Furthermore, there is another weak point of the common power cable configuration, which is the possibility of a total blackout for the subsea distribution system in the case of single point of failure occurrence in the cable.

V. Conclusions

The development of subsea unmanned vehicles is an emerging technology employed for performing various missions including scientific explorations, inspection, repair and maintenance of offshore structures (especially in oil and gas sector), cable laying and, more recently, deep-sea mining. In this paper, different types of subsea vehicles, their power requirements and depth of operations have been explained. However, the main contribution is presenting a quantified methodology to select proper power cables taking into account both electrical and mechanical properties including voltage drop, power loss, reactive power exchanged in the cable, cable current loading, top and bottom tension forces.

Appendix

Table V. The installed power and depth of operation of the surveyed ROVs, trenchers, cable burial tractors and the SMS mining vehicles.

Subsea Vehicle Name	**Depth of Operation [km]**	**Installed Power**	**Contemporary load [kW]** (70% load factor)
ROVs			
Triton XLR [25]	3	125 HP	65
Triton XLX [26]	3	150 HP	78
Triton XLS [27]	3	150 HP	78
Triton MRV [28]	3	150 HP	78
XLX200 [29]	4	200 HP	104
XLX-C [29]	4	150 HP	78
Comanche [30]	2	35 kW	35
UHD 56 [31]	4	200 HP	104
Venum3k-200 [32]	3	200 HP	104
Quasar [33]	4	150 HP	78
Atom [33]	4	100 HP	52
Quantom [33]	4	250 HP	130
Millenium Plus [34]	3	220 HP	115
Hyper-Dolphin [35]	4	75 HP	39
Kaiko MK-IV [35]	7	75 HP	39
Merlin –UCV [36]	3	200 HP	104
Trenchers & Cable Burial Tractors			
Perry XT [37]	3	1200 HP	626
XT300 [38]	3	300 HP	157
XT600 [38]	2.5	600 HP	313
XT750 [38]	1.5	750 HP	391
XT1200 [38]	2.7	1200 HP	626
QTrencher400 [39]	3	400 HP	209
QTrencher600 [39]	2.5	600 HP	313
QTrencher800 [39]	2	800 HP	418
QTrencher1000 [39]	2	1000 HP	522
QTrencher1400 [39]	3	1400 HP	731
QTrencher2800 [39]	1.5	2800 HP	1462
CBT800 [40]	1	800 HP	418
CBT1100 [40]	1	1100 HP	574
CBT2100 [40]	1	2100 HP	1096
CBT3200 [40]	1	3200 HP	1670
SMS Mining Vehicles			
Collecting Machine [41]	2.5	1.8 MW	1800
Auxiliary Cutter [41]	2.5	2 MW	2000
Bulk Cutter [41]	2.5	2.5 MW	2500

ACKNOWLEDGMENT

The authors would like to thank Prof. Erling Ildstad at the Electric Power Engineering Department of NTNU for his valuable comments on the paper content.

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