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Review of Electrical Connectors for Underwater Applications

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Abstract—The history of underwater electrical connectors is relatively new: In 1858, the first transatlantic communication cable was created. Since then, the need for subsea electrical connectors has been growing very fast in the offshore industry. Today numerous companies offer a large choice of underwater connectors and assemblies, and it can be intricate to distinguish the different technologies employed for each of them. However the use, deployment, maintenance, and lifetime of any subsea equipment, from a simple sonar to a wave energy converter, relies on its connectors. Hence the design of an underwater electrical connector is to be carefully looked at, and especially for tailor-made applications that have more specific requirements. To produce a good connector, it is necessary to account for thermal, electrical, and mechanical properties, as well as to determine the best materials that should be used for the application. Finally, connector issues go hand in hand with the deployment and operation of any electrical equipment, and it is of interest to review the different techniques for cable connection, as well as the challenges related to cable layout. Those challenges can be of different nature, but they should all be taken into account for any subsea connection.

Index Terms—Cable, connector, electrical, review, subsea, underwater.

I. INTRODUCTION

IN 1858, the first electrical communication was installed between North-America and Europe through a transatlantic telegraph cable [1]. More than 3200 km of cable, weighing nearly 550 kg/km, were deployed at a depth of often more than 3 km. About 150 years later, the techniques to deploy and protect the cables remain similar. A lot of efforts have been devoted to develop the connectors, which are the weak point of most electrical cables [2], to improve their connectivity and water tightness, simplify their manufacturing process, and decrease their costs.

Despite their variety and the number of its manufacturers, there is little information on the different connectors available on the market and their respective properties. Moreover, there are few papers dealing with underwater electrical connectors. To the authors' knowledge, no review has ever been written on this topic, just some manuals with few references. In addition, it appears that offshore and underwater unsuccessful projects are mostly due to connection failures. Those failures were generally caused by a wrong use of the connector that was inadequate for the environment [3] or incorrectly designed [4]. In the case of underwater communications cable failures, according

to the cable owners, most fiber optic cable failures out to a depth of 400-m result from man-made incidents, i.e., ship anchor drags and fishing—trawling rigs snagging the cable.

This paper aims to give an overview of the type of connectors that exist for underwater and subsea electrical connections. The paper is divided into three parts; in the first part different types of commercial-off-the-shelf electrical connectors will be presented, their performances and defaults will be listed, as well as typical failure modes and their known causes. The second part contains the theory on sealing and on connectors' thermal, electrical, and mechanical properties. The last part provides information on connection procedures and other details about connecting subsea cables with focus on the connection of offshore renewable energy (ORE) farms.

II. BACKGROUND AND TERMINOLOGY

A. Concerned Application Areas

Underwater electrical connections are mainly used in the following domains [5]–[8].

ROV/AUV: The remotely operated vehicles (ROVs) industry is growing and the need for connectors is hence increasing. In particular, the volume and weight of the vehicles are going down and consequently the connectors should meet those new requirements of small size and low weights for the same specifications [9].

Oil and Gas: Oil and Gas industry is the biggest consumer of underwater connectors. Many new challenges occurred with the increasing depth of production and exploration, and with them the issues to develop robust connectors that resist to high pressure, seismic risks, and harsh environment [10].

Offshore Renewables: With the development of many ORE technologies, the need for high-performance connectors is also increasing, and the suppliers are focused on the design of affordable technologies with robust connectivity [11]. OREs have different demands than Oil and Gas industry because they need higher power and extended bandwidth communications; for instance offshore wind transmission is currently done at 33 kV in most countries [12]. This is why a new market for high-voltage connectors is emerging and developing.

Research: Underwater electrical connections have always been necessary for oceanographic, meteorological, and other research activities. The usual requests are tailor-made connectors that suit particular and singular applications [2], [13], [14].

Military/Defense: This sector is looking for high reliability and adaptability of its connectors, due to the variability of the operations, causing dynamic effects and pressure variations on the equipment and the dynamic involved. The connectors require hence extensive performances.

Communication: This industry uses mostly optic fiber for its connections between countries and continents. Those connectors will not

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Fig. 1. Sketch of a basic fluid-filled connector.

be the main focus of this paper, since optical communication has been widely studied in various papers [15]–[18]. In addition, an interesting map of submarine communication links in the world showing the multiplicity of communication routes across the oceans is presented [19].

B. History

The history of underwater connectors can be found in several papers (for example [20]–[22]), but deserves to be written briefly here. There was no real industry of underwater connectors before World War II, and homemade methods were commonly used to create an electrical connection subsea. One of them was to take a regular connector and wrap it with rubber around the junction so it overlapped the connector's sleeve. This tube would then be sealed with strings, and it would work quite well [22].

It was only in the 1950s that the growing number of submarines used for military defense created the need for real underwater connectors. The first ones were of two kinds [i.e., rubber molded (RM) and rigid shell], and they are described in Section III of this paper because they are still in use [21]. The first ones were “dry-mate” connectors, which means that they were to be mated above the surface before being deployed.

In the early 1960s started the development of new technologies to connect and disconnect cables directly underwater: The “wet-mate” connectors. The first type of wet-mate connectors was the pressure-balanced oil-filled (PBOF) connector, which isolates the contacts from sea water by surrounding them with sealed oil chambers. The inductive coupling connectors were developed in the 1970s. In the inductive coupling connector the connectors contain a conductive coil, and each time a signal fluctuates in one of them the other transmits the signal with an induced current. Underwater optical connectors were developed in the eighties, and hybrid wet connectors one decade later [21].

Today thousands of different connectors are available off-the-shelf, each supplier having its own technology.

C. Terminology

According to the ANSI/NEMA CC 1-2009 standard [23], an electric connector is defined as “A device that joins two or more conductors for the purpose of providing a continuous electrical path.”

The plug is the male body and contains pins. The receptacle is the female body and contains sockets. All connectors are equipped with either dummy plugs or dust caps to keep electrical contacts clean when

the connector is not mated, but the dust caps are used only for the surface zone (splash-proof) [24].

A connector contains basically two systems [25], which are as follows.

- 1) The front wet-end system, which is the active part of the connector, and whose role is to create the mating between the two halves.
- 2) The back-end and termination system, that is responsible for the sealing between the cable and the connector.

Both systems can have various number of components depending on the complexity and the technology of the connector.

There are basically two types of connectors: the dry-mate or dry mateable connectors need to be connected and disconnected outside the water; they are less expensive and simpler, with no or few moving parts. The wet-mate or wet mateable connectors, that can be mated subsea, are much more complex because of the need to electrically isolate the pins/receptacles from sea water. We can also distinguish wet-mate and underwater connectors, the first ones being used for shallow-water connections, and the second ones for deep-water operations.

Fig. 1 shows a basic schematic of a connector, here one pin oil-filled.

III. COMMERCIAL OFF-THE-SHELF (COTS) CONNECTORS

A. Main Available COTS Connectors

Here, we present the main types of underwater connectors available on the market. Although each manufacturing company has its own designs and technologies, they can be grouped in four main categories.

1) *Rubber Molded*: RM connectors are the most common and simple connectors and general descriptions of them can be found in [22], [24], and [25]. They are basically cables with male and female terminations that are molded at the conductor's end. The molding material is typically neoprene or polyurethane. Those connectors are generally rated up to 600 V [25] but high-voltage connectors are available up to 3 kV. Polarization is made through the contact of the pins inside the sockets and the molded area provides sealing between the two halves, as well as a strain transition between the contact area and the cable [26].

Having a soft internal and external structure, the RM connectors are unable to control their internal pressure. For this reason it is difficult to unmate them underwater at large depth, the pressure between the pins and receptacles being too high [22]. Moreover, they are subject to risk in the sealing because their material (rubber) is subject to differences of elasticity depending on the temperature. Rubber has also a high

Fig. 2. RM connectors, dry-mate on the left, and wet-mate on the right (where the pins have rubber that can wipe the water off the socket) [27]. The size can vary from 1 up to 5 cm in diameter.

Fig. 3. Twelve pins Bulkhead connector with metallic housing [28].

thermal resistance, which makes the connector unfit to withstand high temperatures in the cable. On the positive side, these connectors are comparatively cheap, light, and easy to manufacture. The dielectric material (here rubber) will not be affected by corrosion and salt water. RM dry- and wet-mate connectors are shown in Fig. 2.

An evolution of the RM connectors is the plastic molded (PM). They also have a very simple structure, with epoxy reinforced glass fiber molded directly on the conductor, which provides a higher resistance to mechanical stress than rubber. However, they are more brittle than the RM connector. The material is also sensitive to temperature changes.

2) *Rigid-Shell or Bulkhead Assemblies*: By molding a rubber connector into a rigid body, substantial strength and stability are provided along with a better possibility for coupling and locking. The connector will then be able to withstand harsher environments. The locking is performed by screwing the two half-shells and the sealing is provided by O-rings. The voltage rating usually goes up to 600 V for regular connectors, as for the RM and PM connectors, and up to 3 kV for more specifically designed connectors [5]. The rigid-shell assembly is small in size and low in cost, but also heavier than the molded connectors. The bulkhead materials are typically metal, plastic, or glass fiber reinforced epoxy. Fig. 3 shows a metal bulkhead connector.

The drawback with rigid-shell connectors is the pressure differential that applies between the outside of the shell and its interior, which could lead to early breakage. The void contained in the assembly is susceptible to cause condensation of moisture in the contact area. Moreover, a metallic bulkhead can be subject to corrosion. Special care is also needed for the molding between the shell and the cable at the back-

Fig. 4. Scheme of a PBOF connector [25].

end of the connector. This interface is particularly subject to damages caused by cycling loads, and especially where different materials are used together. If welding is used, the material must be adequately protected from the welding temperature [26]. More information on rigid-shell or bulkhead assemblies can be found in [8], [21], [22], [24], [25], [27], and [28].

3) *Fluid-Filled Underwater Mateable*: This type of connector uses a chamber filled of a dielectric fluid, typically oil, to isolate the contact from seawater. Seawater is wiped off as the conductive pins go through a diaphragm in the face of the receptacle [26]. These connectors are generally physically larger and more expensive than the standard metal shell electrical connectors, but they are inherently more robust [25] by design and experience. Their high price is mostly due to the complexity of the assembly with the different moving parts.

In this case, the connector is not exposed to pressure differentials because the oil inside the cavity and seawater are balanced. As a consequence, mating or demating the connector can be performed at any depth with no extraordinary force. Since they are immersed in oil, the pins are not subject to corrosion, and moreover they can be electrically charged before mating.

Fig. 4 is a schematic of one of the first PBOF connector from [25], while Fig. 5 is a much newer PBOF connector from 2003 from the company SEACON, Bellville, TX, USA [27], [28].

One of the difficulties when designing oil-filled connectors is to provide seals that allow the pins to be inserted repeatedly inside the oil chambers without losing the oil or allowing water intrusion. One possibility, as described above, is to wipe the water off the pins with help of a diaphragm installed ahead of the receptacle. Another widely used design uses dielectric pistons, where each socket is connected to a spring that is pushed inside when the pin is penetrating the receptacle.

PBOF connectors are still evolving and some interesting designs are presented for example in [2], [20], [21], and [29].

4) *Inductive Coupling*: In the inductive coupling connectors, each half contains a coil that allows electrical current to pass from

Fig. 5. SEACON PBOF connector (dimensions in mm) [22].

Fig. 6. Noncontact wet mateable connector, approximately 25 cm long and 9-cm diameter [2].

the female to the male and vice versa. The great advantage is that no conductive parts are exposed to seawater [21]. Additionally they are mechanically simple and easy to mate and demate since no pin insertion is required. They are not so commonly used for two main reasons: they are usually rated for low power (<20 W), and they only allow ac current [22]. This is why they are mostly used for data transfer only.

Baer *et al.* [2] and Granger *et al.* [30] described an innovative non-contact wet mateable connector, which is presented in Fig. 6.

B. Assemblies (Nonunmateable)

The term “connectors” includes the products that allow a connection between electrical cables, but without the possibility to mate or demate them. Among those products we distinguish terminations or penetrators [31], which connect cables to a device, an equipment, or a pressure housing, and joints that link two cables together [32], [33]. Cable glands will protect the cable from water insertion but are neither rated for deep submerged use, nor for dynamic applications. T-splice and Y-splice will group and put together two cables into one, respectively, in a T- or a Y-form. Finally, we find field installable termination assembly [34]. They allow a connection on site directly underwater, which is very advantageous. Fig. 7 shows examples of a cable termination and a Y-splice.

A nonexhaustive list of dry- and wet-mate connectors manufacturers is given in [35] and Table I summarizes the main characteristics of the above listed types of connectors.

IV. CONNECTOR DESIGN

Although many different types of connectors are commercially available it is very common to purchase tailor-made ones to fit exactly the project's needs. One reason for this is simply that the choice of connectors is not large enough to cover the demand, and another reason is that the reliability of the connectors is so important for some underwater projects that they need to fit exactly the requirements. In many cases,

Fig. 7. Cable termination [31] and Y-splice [24].

once the connector is deployed, the time and cost needed for repairing or replacing it are simply too high to be considered; the connector must withstand its whole lifetime without any failure. This is why special design is often necessary for ac power cable, optical communication, permanent joints as splices and terminations, or other connectors that must operate for a long time without maintenance.

The design of a connector is highly related to the design of cables, and the interested reader is hence advised to read through references [36], [37].

A. Thermal Design

The thermal design of subsea connectors aims to define the right housing size so the required power can be transferred from one cable to another without exceeding the temperature limits of the conductor

TABLE I
SUMMARY OF COTS CONNECTOR TYPES AND THEIR CHARACTERISTICS

Connector	Mating type	Voltage/power rating	Cost	Pros
RM	Dry	Up to 1 kVAC/ 850 VDC	*	Cheap and available
Rigid shell/Bulkhead	Dry	Up to 3 kVAC/ 2.55 kVDC	**	Robust, comparatively cheap, easily available
Oil-filled	Wet	Up to 3.3 kVAC	***	Reliable, easy to deploy and to maintain on site
Inductive coupling	Wet	20 W	***	Easy to deploy and maintain on site, no conductive part exposed to seawater
Assemblies	Dry/Wet	Up to 600 V AC/ 510 V DC	**	Allows to deploy equipment before connection

or its environment. The connector's size mainly depends on the outer diameter of the cable and this is why it is necessary to look into the power cables' thermal properties to design or choose the appropriate connectors [37], [38].

The most basic thermal model for dc power cables corresponds to a single core conductor. Heat is produced as current passes through the cable, and this heat is transferred from the wires to the external environment (here water) through the successive layers of the connector. The ohmic losses in the conductor can be written as

$$P_L = RI^2$$

where P_L is the power losses in W/m, R is the conductor's electric resistance in Ω/m , and I is the current passing through the conductor in A.

R depends on both the conductor's material (usually copper or aluminum) and its cross section. The thicker the wire the smaller the resistance. Under steady-state conditions, all the heat generated in the conductor must flow to the outside environment through the cylindrical dielectric insulation. The relation between the temperature drop across the connector insulation, the power losses and the thermal resistance of the insulation wall can be described as

$$\Delta\theta = P_L R_T$$

where $\Delta\theta$ is the temperature drop, P_L is the power losses through the conductor, and R_T is the thermal resistance of the insulator, with

$$R_T = \frac{\rho_T}{2\pi} \ln \frac{D_o}{D_i}$$

where ρ_T is the specific thermal resistivity of the insulation material, D_o is the connector's outside diameter, and D_i its inside diameter.

If the insulator consists of several layers, the temperature drop can be calculated as the sum of the different temperature drops between each layers

$$\Delta\theta = \sum_n \Delta\theta_n = \sum_n P_L R_{T_n} = P_L \sum_n R_{T_n}$$

where R_{T_n} is the thermal resistance of the insulation wall's n th layer, described as in the above equation.

Values of thermal resistances for different materials used in the isolation of electrical cables are presented in Table II.

Temperature changes due to load cycling induce weaknesses in the material's properties, as strength and elasticity, which drastically reduces the connector's lifetime.

For ac cables additional losses are due to electro-magnetic factors, as the skin effect or the corona effect. These factors, although impacting thermal studies, will be discussed in the electrical properties, in Section IV-B.

TABLE II
THERMAL RESISTIVITY OF ISOLATING MATERIALS FOR ELECTRICAL CABLES

Material	Thermal resistivity (Km/W)
Paper insulation, oil-filled cables	5.0
PPL (polypropylene layers, insulation material)	5.5
XLPE (cross-linked polyethylene, used for extra-high voltage cables) or PE thermoplastic (polyethylene)	3.5
EPR (ethylene propylene rubber) for cables ratings above 3 kV	6.0
Outer serving	
PE (polyethylene)	3.5
PVC (polyvinyl chloride)	6.0

B. Electrical Properties

The electro-magnetic field distribution is the most influencing factor in the failure of insulation systems, and these failures may be boosted by the presence of pollutants such as water or moisture [39].

For ac cables, the alternating magnetic field causes the skin effect around the conductor, making the current density higher close to the conductor's surface, and lower at its core. The larger the conductor's area, the more important this skin effect. In addition, another effect called the proximity effect is created by the closeness between the wires when the cable contains several cores (such as three-phase cables). The consequence is an inhomogeneous current density in each wire, the current from one core trying to stay as far as possible from the others. These two effects increase the power losses in the cable and need to be taken into account in the calculation.

Although electrical design affects all connectors, the ones that need specific studies are mostly used for power transmission, at high voltage (>1 kV), or extra-high voltage (>275 kV), because at this voltage level, if the strength of the electrical field exceeds a certain value, the effect called the corona effect occurs [39].

This effect produces audible noise, radio interference, power losses and also generates harmful chemical compounds such as ozone and nitrogen oxides [39]. Therefore, the corona effect is a focus of concern, and several studies are being conducted to investigate this phenomenon. Unfortunately, the corona discharge is a very complex phenomenon, which is very difficult to model since it depends on several variables, including experimental arrangement geometry, surface roughness, operating voltage and environmental conditions (as pressure, temperature, humidity, salinity). To reduce the strength of the electric field, corona shields are used on electrical connectors. By this way, corona activity including power loss, television, and radio interference and audible noise levels are significantly reduced [11], [39].

For low-voltage connectors, the electrical design must take into account the choice of amperage and how the power transfer is done. It will give the type of connector (electrical, optical, hybrid), its size and diameter, the number of necessary pins/fibers, and the type of contact.

Fig. 8. Characteristic curves of the endurance to pressure cycles depending on the ambient pressure [40]. 10 000 psi corresponds to approximately 70 MPa.

If the connection must be done with power on, then a wet-mate technology must be used, if not, then the possibilities of design are larger (at least concerning the electrical side).

Electrical insulation is also an important issue to protect current transfer from the conductive seawater. In that matter, the choice of material and the mechanical seals are critical factors and will be discussed in Sections IV-C and IV-D.

C. Mechanical Properties

Underwater connectors must withstand the stresses due to manufacturing, transportation, deployment, and lifetime subsea. Dynamic forces apply on the connector during the deployment and potential maintenance for static equipment, and all the time of operation for underwater vessels. Hydrostatic pressure is present during the connector's whole lifetime and the magnitude depends on the water depth. Too little precaution in the mechanical design could lead to damages that will force early maintenance, replacement, or decommissioning before the connector's electric lifetime's end [37].

The major contribution to mechanical failure in an underwater electrical system is cycling from low to ambient system pressure, the more severe conditions occurring with the higher magnitude of pressures [40]. These pressure variations can cause collapse of void and pressure barriers, fatigue of conductors, and breaking of bonds and sealed parts.

Fig. 8 presents the typical endurance to pressure cycles' function of the ambient pressure for two cables with different cross sections. Endurance to pressure cycles can be defined as the capacity of a component to withstand fatigue loads created by cycles of pressure differences. The bigger the cable, the lesser the resistance to the cyclic loads.

The connector's mating and unmating procedure is also a source of great stress that will increase fast depending on if the connector is to be plugged once or a few times (power cables), or a large number of times (ROV connectors).

The critical mechanical aspects related to connectors are the following.

- 1) The connection between the conductor and the pin/socket.
The connecting of cable conductors to contact components is generally performed by crimping or soldering. A bad connection could lead to a short circuit or a breaking, and this operation is especially sensitive for miniaturized connectors with many pins.
- 2) The bonding between the connector and the cable.

Usually the connector's sleeve is molded on the cable, but depending on the type of connector one could also use bonding agents [41], [42] or welding if some metal parts are involved. It is absolutely essential that the bond prevents from any water ingress between the connector and the cable.

- 3) The contact plug-receptacle.
Depending on the procedure to connect the two halves, the mating force will typically vary from ca. 100–200 N, to 500–1000 N. For wet-mate connectors, the pressure at great depth makes the connection forces even larger. The mechanical design should include a study on the contact plug-receptacle to allow an insertion of the pins into the sockets within a certain range of forces. The required force should not be too high so that contact can be performed by a human or a machine, and not too low for insuring reliability.
- 4) The sealing between each connector-half or between the joint and the device/junction box (see e.g., [43]).

It is commonly done using O-rings and Flitney [44], [45] gives detailed information in this matter. However some other methods can be interesting for permanent joints, such as the use of pressure gasket-plates, internal plugs, or internal feedthrough [40]. Often one would multiply seals inside the connectors as backup protections.

Once the contact is made the locking would typically use threaded locking sleeves, although sometimes the contacts lock with no additional tool, as the RM connectors whose rubber helps the bonding of the two halves. Some connectors are equipped with only a small plastic band that is slipped around each half when mated. It is not as reliable as the screwing sleeve, but it saves weight and size [46].

- 5) Weight and Size.

With the miniaturization of electronics and electrical components came the need for smaller connectors and thinner electrical cables. Offshore activities have been subjected to the same development and the weight and size of subsea connectors are now becoming critical mechanical design factors. In this matter, innovative products have appeared on the market, and many suppliers offer dry- and wet-mate off-the-shelf connectors in a normal, mini or even micro format with approximately the same electrical and thermal properties [27], [28]. Progress in the sector is mainly due to innovations in material science with the development of both light and strong materials, and this will be discussed in Section IV-D.

D. Material Choices

Different connector types would require different materials, but the same properties apply: high degree of dimensional stability, high impact strength, low mold shrinkage, low water absorption, high compressive strength, and nonflammability [26]. Common used materials are the following.

- 1) Elastomers and their varieties are used in many types of connectors. They are very useful because they are elastic, with a high compressive strength and low water absorption coefficient. Such a rubber material could typically be polyurethane or neoprene. Those materials are commonly used to wrap the connector and cable together. However, it appears that rubber can be employed as a cement, as in [47], where the material 3140 RTV, a silicone-based rubber, is used to bond a splice to a cable.
- 2) Plastics are known for their low-water absorption coefficient. They can be utilized as a shell in the bulkhead assemblies. Polymers, on the other side, are used as coating, adhesive, or covering

TABLE III
EPOXY RESINS SELECTION FOR UNDERWATER USE (FROM [48])

Manufacturer	Product	Comments/Use
Rescon	UV-L	Bonding aid/adhesive
Colebrand	CXL 600	Small cracks injection
	CXL 78T	Small splits, adhesive
	CXL 194	Adhesive
Sika Inertol	Sikadur 53LV	Low viscosity injection

materials, and some types can be used underwater [48]. They include resins that allow a bonding between the connector and the cable, or between the shell and the plug. A few epoxy resins for subsea use are suggested in Table III.

- 3) Composites, and in particular glass fibers reinforced epoxy can serve as housing for the connector. They are much stronger than rubbers.
- 4) Metals should be noncorrosive or a sacrificial anode should be added to the system (see for example ref [49]).
- 5) Dielectric fluids, or oil, are used to watertight the pins and sockets and seal them from seawater. Moreover they keep a pressure balance between the inside and outside of the connectors, usually with the help of a vent that adapt the amount of oil inside the cavity, or a piston that counteracts the space containing oil with the water pressure.

The challenges for those materials are their capacity to withstand high pressure, corrosion, and seawater absorption. Buggy and Kojima [50], [51] give good insights in the choice of materials used for electrical connections, as well as failure analysis concerning corrosion.

In fact, thermal properties are always related to either electrical or mechanical design. Many studies analyze the effects of one property on another, for example by combining high-temperature cycles and high-power transfer [52], [53], or by modeling thermal effects due to electrical loads [54], [55], or with thermo-mechanical studies [56]. Some other articles study the influence of electrical and thermal properties on a connector's lifetime and aging capacities [57], [58].

E. Specifications for Underwater Connectors

The design and development of underwater electrical connectors include many steps: design and feasibility studies, prototyping, concept reviews, critical design reviews, failure mode, effects, and criticality analysis (FMECA), final design reviews, test readiness reviews, detailed qualification programs, and pilot project deployments.

All those steps require specifications and qualifications, but so far only a few industry standard specifications for underwater connectors exist. However, there is a variety of specific requirement documents created by oil and gas operators and associated major equipment providers [59].

One can find two military specifications, MIL-C-24217 and MIL-C-24231, which cover dry-mate style electrical connectors for underwater use [60], [61]. Both of these military specifications were developed in the 1960s and were last revised in the early 1980s [4]. MIL-C-24217 specifies the use of glass seals on the electrical conductors of the receptacle assemblies. MIL-C-24231 is a specification on molded assemblies that are contained in a metal housing.

API 16A and API 16D are two specifications for underwater drilling equipment, and API 17E specifies the use of subsea umbilicals.

ISO 13628-6 was created by Oil and Gas industries, and concerns the design and operation of subsea production systems.

TABLE IV
ADVANTAGES OF WET-MATE COMPARED TO DRY-MATE CONNECTORS
CONCERNING THE CONNECTION PROCEDURE (FROM [65])

Dry-mate drawbacks	Wet-mate advantages
Manipulation of cable	Disconnection at the bottom (easiness and shortness of operation)
Additional cable length	Reduced lifting capabilities
Amount of cable to be lifted	Cable connection independent from device installation
Cable cannot be fixed to the seabed	

Finally, STATOIL TR2390 is a specification on electrical/optical connectors and jumpers for subsea control systems [62].

V. CONNECTOR DEPLOYMENT AND OPERATION

A. Connection Procedure

There is no established specification for the procedure of performing an underwater connection. However, there are industrial working groups such as Subsea Fiber Optic Monitoring (SEAFOM), which are working on creating industry recommended practices for subsea interconnected systems [20], [23], [63].

The simplest connection procedure is the dry-mate connection that is done manually onboard. However, this procedure means that the length of cable to be lifted on each side of the connector will be approximately three times the water depth with associated problems such as heavy lift and stress on the cable.

Wet-mate connections can be performed with help of either ROVs, divers, or stab plates. Divers can only operate in shallow water and for a limited amount of time (for instance 40 min for a 25-m-deep operation), which reduces drastically the possibilities. They could operate up to 300-m deep, but then the procedure becomes expensive and hazardous as the divers would work in a team in a pressurized cabin, taking turns for up to one month. On the other hand they are fast and precise. However, the main issue related to diving activities is the risk taken associated to working hazards. Any subsea activity that includes human work is subject to a certain risk, and it increases with the depth and distance of the working station, but also with the weather. ROVs can be used in deep and shallow water, but they are much slower to operate, which increases the time of the procedure. Their efficiency also depends on weather conditions, namely winds, currents, waves. But using ROVs is obviously less risky because no human lives are at stake.

Finally, stab plates can be advantageous for grouped connections. The half-connectors are attached to two different plates that contain many of them, and it allows us to mate several connectors at once, sparing time and space [64].

Wet-mate connections surpass dry-mate connections in many ways, and Table IV lists some of those differences.

However, wet-mate connections are of higher costs, especially with ROV installation. They need a frame support to be grasped by the ROV, which increases the weight and complexity of the connector, as seen for example in the Nautilus products from Teledyne [66], as shown on Fig. 9.

Beurthey [65] and Remouit [67] present two innovations to connect dry-mate connectors underwater: the first one uses air-filled pockets that create a dry environment surrounding the connector, as shown in Figs. 10 and 11. Fig. 10 is a computer-aided design (CAD) file of an underwater substation whose role is to collect electricity coming from

Fig. 9. Nautilus connector, ROV mateable (the length A is between 11.9 and 21.9 mm) [66].

Fig. 11. Photograph of a diver filling the pocket with air to perform the dry connection [67].

Fig. 10. CAD file of the air pockets for underwater cable connections at the substation of Uppsala University, Uppsala, Sweden, Lysekil project, 2.2-m height and 1.5-m diameter [67].

different wave energy converters (WECs). It is approximately 2.2 m high and 1.5 m in diameter. Each of the WECs has four cables that are ended with dry connectors. Those connectors are enclosed in an “air-pocket” that is open underneath. When the diver comes to plug the connector, he or she inserts pressurized air in the air-pocket to create a dry environment around the connector. This allows the dry connection, and once the cable is plugged, the pressurized air flow is stopped, allowing the water to go back in the air-pocket. Fig. 11 shows a picture of this connection procedure. The hand of the diver, in the bottom part of the image, is inserting pressurized air in the glass box (that can also be seen on Fig. 10) to create a dry environment around the connector to able the mating/unmating.

The second innovation employs an oil-filled box to seal the two halves of the connector before removing of the caps and mating, as shown on Fig. 12.

The use of junction box is also common for oceanographic and observation projects, as seen in [29], [55]. A junction box serves as a hub between one or several devices and the shore. It enables both communication and power supply from and to the equipment, and has the advantage of channeling all the connectors to one single unit.

Fig. 12. Mated connector inside oil-filled clamshells tool (size: 40 cm long and 10 cm wide) [65]. The connector (blue and pink parts) is enclosed in the oil-filled clam-shell (transparent yellow). The connection is done with help of the two green components moving along the sliders to mate/unmate the two halves.

B. Connection Layout

With the emergence of ORE, the question of connecting multiple cables in an optimal layout was raised. The vast majority of ORE farms requires many units working in arrays to produce sufficient power, hence the need for multiple connections within the same area. Several strategies to optimize the cable layout for smooth subsea connections have been investigated. Other related challenges include maneuvering in a farm of devices and identification and location of connectors and cables in a complex network of cables.

The main design criteria for a connection layout are the following:

- 1) fault tolerance;
- 2) ease of assembly and management;
- 3) reasonable costs.

The fault tolerance factor can be translated as the need for a least number of connectors since they are an important source of failure. Although they facilitate the assembly they should be kept as a minimum. The ease of assembly and management will be obtained by a division of the system into subsystems that are easy to deploy, test, and maintain, without disconnecting the whole farm/grid [11], [68]. As a consequence, the costs of operation and maintenance will decrease, but those criteria must also meet other requirements that impact the project. These requirements can be environmental: for instance the two devices must be kept at respectable distance from each other in order for fish and marine mammals to go through the array. It could also be that a certain area is to be preserved and cannot be used. Technical requirements could come from the seabed or soil's quality, which would command a specific layout for the cables and devices. One can also

raise the requirements concerning security matters: for example safety in the deployment, ease of access to maintenance, or necessity to avoid natural hazards [3].

Offshore renewable energies are facing additional challenges related to optimization of energy absorption and farm layout. Depending on the incoming wind/waves/current parameters your park will gain in efficiency by following a specific pattern (see for instance reference [69]), and this model can be conflicting with the optimal connection layout.

Cabling layout optimization has been studied in [70]–[73], while [74] and [75] concern power cable connection in general.

C. Reliability

The majority of underwater connection projects, and especially within big offshore industries (offshore wind, oil and gas, etc.), includes a reliability study that will analyze the failure possibilities in the system, and their consequences in terms of time, costs, and security. The most seen method among the investigations on underwater connection is called FMECA. It allows evaluation of all possible failure modes for a connector/connection and study of both the probability of occurrence of these failures, from very unlikely to frequent, and the severity of their impacts on the system, from minor to catastrophic [62]. The FMECA is typically performed at an early stage of the project, and the predictions would be first qualitative, in case of lack of data, and evolve to quantitative measurements, with more or less details. It is indeed possible to survey the system in its whole (connector manufacturing, deployment, connection procedure) as well as to deepen the study up to the smallest part or component (pin, socket, and material) [76]. The resulting tables serve as a feedback to improve a design or a procedure. They are meant to be used ahead of the project, however, the experience of failures will help enhancing the process and prototypes.

One innovative method for reliability estimation is described in paper [77], using a Weibull-covariate based model. Several other models predicting mean failure rates of different underwater systems are also presented in this paper, as the accelerated life testing model, Monte Carlo's models that are based on the failures' history, or proportional hazard models.

Finally, Vedachalam *et al.* [78] give a detailed insight of the complexity of reliability modeling depending on the connection layout for a substation used in oil and gas industry.

VI. DISCUSSION AND CONCLUSION

Although underwater electrical connections have existed for more than 150 years a relatively few number of papers have been published on this topic. This is caused by the necessity for industrials to patent any new product and hence keep a complete confidentiality on them. Underwater electrical connectors have always been designed by industries and research institutes have usually not taken part in the process. Hence publications in this field are scarce but valuable.

It is interesting to mention that a nonnegligible part of the articles reviewed here were written in the 1970s and 1980s and are still up-to-date and relevant, which means that many challenges related to subsea connection remain. By investigating today's articles, it can be noted that the same causes of failures persist over the years: corrosion, leakage, or bond failures. Another reason for the recrudescence of papers from three and four decades ago compared to now might also be that current connectors are more efficient and reliable than before, and also cheaper, hence of less concern.

There is today a large offer for directly available connectors, especially optical fiber connectors and hybrid joints. This variety allows a multiplicity of underwater projects to emerge, which before were set

aside for oil and gas, military, and telecommunication sectors. For example, the production of mini and micro connectors came together with the emergence of small ROVs that can be used for research projects and oceanographic studies with little funding. Those COTS connectors are presented in Section III.

Despite the increase of available underwater electrical connectors the need for tailor-made mating concepts remains. They are such a key in the system reliability that it is essential to purchase the best item, to fit the requirements as well as possible. Particularly, the projects concerning power cables, telecommunication, deep water industry, or military, must not fail, and the connectors are sometimes to be deployed once, with no maintenance for their whole lifetime, usually around 20 or 25 years. Consequently they need a unique design that merges the right properties in the electrical, thermal, and mechanical areas. There are many critical factors in these different aspects, explained in Section IV, and it illustrates the complexity of some connectors.

From this review, one must emphasize that the emergence of new offshore and subsea markets requires enhanced development of COTS underwater electrical connectors. As said before, OREs have specific requirements: high-voltage connections at a moderate depth compared to Oil and Gas (up to 200 m), with both dynamic and static cables. The market for OREs is growing fast and the lack of adapted connectors could hinder its full development. The same appears for small ROV connectors: although growing, the demand for small and light ROVs working at moderate depth does not meet the supply in terms of size, weight, costs, and reliability of COTS connectors.

It is relevant to point out the increasing number of papers studying optimal procedures and layouts for connection architectures. The development of offshore renewable energies comes with the need to decrease costs and facilitate underwater operations, due to the multiplicity of devices in one farm (unlike in the Oil and Gas industry). It could be also said that after a first phase whose objective was to produce reliable underwater electrical connectors, it is now most important to decrease their costs and produce smaller products in larger quantities. The popularization of scuba diving for example, the emergence of companies selling private ROVs, or the fast growing subsea communication industry, will surely accelerate the dissemination of those valuable underwater connectors.

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