Power and Submarine Cable Systems for the KM3NeT kilometre cube Neutrino Telescope.

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Abstract

The KM3NeT EU-funded consortium, pursuing a cubic kilometre scale neutrino telescope in the Mediterranean Sea, is developing technical solutions for the construction of this challenging project, to be realized several kilometres below the sea level.

In this framework a proposed DC/DC power system has been designed, maximizing reliability and minimizing difficulties and expensive underwater activities.

The power conversion, delivery, transmission and distribution network will be described with particular attention to: the main electro-optical cable, on shore and deep sea power conversion, the subsea distribution network and connection systems, together with installation and maintenance issues.

I. INTRODUCTION

The KM3NeT consortium [1], including members of the ANTARES, NeMO and NESTOR collaborations, is developing a kilometre cube-scale neutrino telescope for the Mediterranean sea with associated nodes for deep sea sciences.

The construction of such a detector will require the solution of technological problems common to many deep submarine installations.

Several hundred vertical detection units (DUs) containing photomultipliers will be deployed on a seafloor site up to 100 km from the shore and several kilometres below sea level

The power system is composed of an AC/DC shore power feeding station, a management and control system, a standard, single conductor 10 kV DC-rated electro-optical telecommunications cable with sea-water current return and a distribution network to deliver power to the neutrino telescope. On the seabed specially-developed DC/DC converters will reduce the transmission voltage to 400 V for distribution to the DUs. The estimated total power is about 50 kW. The estimated bandwidth for the full data transport system is of the order of 100 Gb/s. For the deep sea sciences associated infrastructure the equivalent numbers are less well defined but estimated to be less than 10 kW and 100 Mb/s.

The sea-floor network will consist of several junction boxes linked by electro-optical cables to the telescope DUs and to the deep sea sciences nodes. The final design of the network is still under development and will incorporate extensive redundancy to mitigate single point failures.

The design requirements for an ocean observatory site-to-shore cable are compatible with standard capabilities of telecommunications cables, for which a wide range of industry-approved standard connection boxes, couplings and penetrators exists, and which can be adapted to interface with scientific equipment.

Underwater connection technologies, available in the telecommunications, oil and gas markets - including deep-sea wet-mateable optical, electric and hybrid electro-optic connectors - have been adapted and developed to fulfil the project requirements.

The installation and maintenance operations for such detectors are difficult and expensive. In the deep-sea system design special attention is being paid to maximizing reliability and minimizing underwater operations. All components must survive both the mechanical rigours of installation (torsion, tension due to self-weight and ship movement) and must have high reliability and long lifetime under the extreme seabed conditions (high ambient pressure of 250-400 bar, an aggressive and corrosive environment, lateral and torsional forces due to deep sea currents etc.).

The various technical aspects of this unusual power supply system are discussed in the following sections.

II. CABLE POWER TRANSMISSION CONCEPTS

For undersea observatories, both AC and DC power systems are viable and have their particular advantages and disadvantages. Although, even at conventional AC frequencies (50 Hz) cable shunt capacitance requires inductive compensation, an AC power system allows for the use of transformers in the shore and deep sea nodes and efficient high voltage cable transmission. Power interruption is simpler than in a DC system. Furthermore, DC systems have insulation problems that have no counterpart in AC systems; long-term high voltage DC excitation can cause eventual breakdown of solid cable insulation. Therefore, although DC is conventionally used on long-haul undersea telecommunications cables, AC alternatives are also being considered.

For a qualified decision, the power system must be evaluated taking into account the cables, transformers, DC/DC converters, rectifiers, the required voltage stability and the level of short circuit capability. Each item is likely to impact significantly the total price of the power transmission network. Considering the power required and the distance over which it must be delivered, the use of 10 kV nominal voltage is unavoidable. The maximum voltage that can be applied to a cable is limited by insulation breakdown. A maximum of 10 kV is typical for undersea telecommunication cables and is considered as an upper limit.

The current-carrying capability depends on the conductor heating and the voltage drop. The resistance of a typical telecommunication cable is around 1 Ω/km so that over the distances typical for KM3NeT the current is limited to around 10 Amperes. Power can be delivered in the following ways:

- Three-phase AC (multi-conductor cable)
- DC with cable current return (multi-conductor cable)
- DC with current return through the sea (conventional single conductor telecom cable)
- AC mono-phase with current return through the sea (conventional single conductor telecom cable).

III. MAIN ELECTRO-OPTICAL BACKBONE CABLE

The design requirements for an ocean observatory site-to-shore cable are compatible with the standard capabilities of telecommunications industry components which can be readily adapted to interface with scientific equipment. The low failure rate among the large number of such components in service suggests mean times between failures of several thousand years. As standard, a submarine telecommunications cable has to provide a service life of at least 25 years. It must be easy to deploy and repair at sea. The longevity of the installed cable depends on minimising the strain induced on the optical fibres during the dynamics of installation and the long-term seabed environment of high ambient pressure, abrasion risks, unsupported spans, etc.).

The cost of a submarine cable repair at sea is substantial. However, since 1999, under the Mediterranean Cable Maintenance Agreement (MECMA) cable ships, fully equipped with Remote Operated submarine Vehicles (ROVs), are maintained on constant readiness at Catania (Italy) and La Seyne-sur-Mer (France), (Figure 1). These ships provide repair services for subsea cables owned by member organisations (cable operators: around 44 as of 2009). The insurance character of this agreement offers members a repair capability for an affordable yearly contribution in proportion to the relevant cable mileage. Two of the pilot projects are members of MECMA.

The five major submarine cable manufacturing companies have formed the Universal Jointing Consortium which offers qualified and proven jointing techniques for a wide range of cable types ("Universal Joint" (UJ) and "Universal Quick Joint" (UQJ)). MECMA ships support universal jointing.

Virtually all reported submarine cable failures are due to human activity (Figure 2)- notably fishing and anchor falls in shallow water - although natural chafing, abrasion and earthquakes in the deep ocean also occur, as shown in Figure 2. To mitigate these risks, careful route planning is essential, and sea-bed burial is used where circumstances require it.

Fig. 1. The MECMA consortium with the two cable-ship operatoring bases and storage depots.

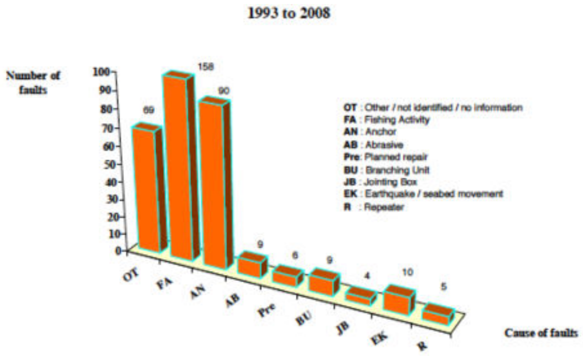

Fig. 2. Submarine cables: causes of fault. (MECMA 2008).

Submarine cable armouring is selected to be compatible with the specific route; therefore the cable mechanical characteristics are an integral component of the overall system design. Submarine telecommunications cables can be equipped with virtually any fibre type and any reasonable number of fibres. At present all the major cable manufacturers deliver telecommunications cables with a number of fibres that does not routinely exceed 48. This is mainly due to the advent of Dense Wave-length Division Multiplexing (DWDM) technology and to the requirements of simplifying the cable mechanics. The fibre types used for submarine transmission are optimised for minimum attenuation over the full C-band (1530-1570 nm) with dispersion characteristics that depend on the application. The cable optical properties are an integral part of the optical communications system specification.

Fig. 3. Examples of different armouring on submarine cables.

Many types of submarine telecommunication cables are commercially available. The design varies depending on manufacturer, fibre count, power requirements, and the external protection. Figure 3 shows a range of mechanical configurations of telecommunications cables.

The armouring is strongly related to the characteristics of soil, water, marine current, depth and installation methods

The interface between a cable and the submerged infrastructure is complex. Not only must the connection provide load transfer through a mechanical discontinuity in the cable, but it must also maintain electrical insulation relative to the sea potential, while supporting the safe connectivity of both optical fibres and electrical conductors. Any submerged component, such as a telecom repeater, is connected to the cable through so-called extremity boxes, each effectively forming one half of a cable-to-cable joint.

a. Cable Design Examples

The design is likely to be driven by availability from telecommunications cable suppliers. In the following sections some presently available cable designs are discussed, together with the different power options. These should be seen as examples of what is possible.

b. Monopolar Power Delivery

A monopolar system incorporates a current return via the seawater and will generally result in the smallest cable dimension and weight. Due to the extremely small resistance in the sea return this system has low power losses. Cables usable for this system are in fact the most commonly used in the telecommunications industry. To allow for the current return via the sea this system must incorporate sea electrodes both at the shore and in the deep sea. An example of such a cable is shown in Figure 4. The most significant technical problem with a DC monopolar system is the danger of corrosion of neighbouring structures and installations. Due to electrochemical reactions on the sea-return electrodes chlorine gas may be generated. Where such a system is used these issues must be addressed.

c. Bipolar Power Delivery

In a bipolar system a return conductor is required. This can be achieved by incorporating a return conductor a single cable or having a separate return cable. The choice will be driven by the relative cost. Figure 5 illustrates an example of a submarine cable [3] which contains four conductors; two for supply and two for return.

d. Three-Phase AC Power Delivery

In this system three conductors which share the current are required in the cable. An example of a cable usable for this system [3] is shown in Figure 5. Such a system requires a balancing of the loads on each conductor. If this is not fully achieved extra power losses are incurred.

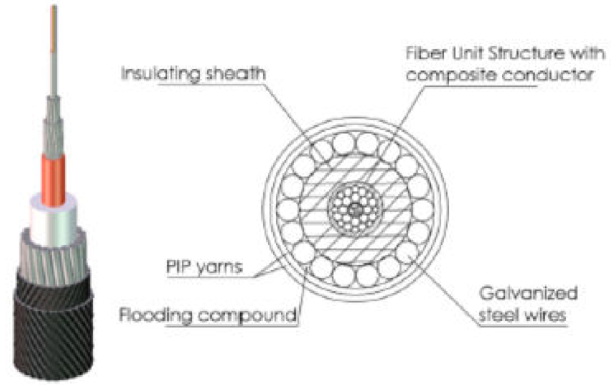

Fig. 4. Standard monopolar submarine cable – internal structure.

Fig. 5. Bipolar submarine cable example.

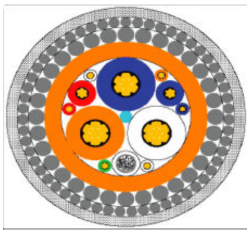

Fig. 6. Three-Phase submarine cable example.

IV. A POWER TRANSMISSION SYSTEM EXAMPLE FROM THE NEMO PHASE-2 PILOT PROJECT

A site location located on a 3500 m deep abyssal plateau approximately 40 NM south east of Capo Passero, Sicily, (36° 20’ N; 16° 05’ E) has been proposed by the NeMO collaboration for the installation of a km^3– scale detector. The oceanographic and environmental properties of the site have been measured in more than 30 sea campaigns over nine years. The NeMO Phase-2 project is under realization on this site and will allow the installation of prototypes of km^3 detector components at 3500 m, also providing an on-line continuous monitoring of the water properties.

a. The backbone cable

The backbone cable is a DC cable, manufactured by Alcatel-Lucent [2] and deployed in July 2007. It carries a single electrical conductor, that can be operated up to 10 kV DC allowing a power transport of more than 50 kW, and 20 single mode ITU-T G655-compatible optical fibres for data transmission. The cable total length is about 100 km.

b. On shore power feeding equipment

The shore Power Feeding Equipment, (PFE), is an AC-DC converter providing 50 kW at 10 kV DC with sea current return. The PFE, from HEINZINGER Electronic GmbH has the following main characteristics:

Input	3 phase 400 V
Power Factor	> 0.9
Output Voltage	
Negative Polarity	0 to 10 kV
Positive Polarity	0 to +1.5 kV
Regulation	< 0.1 %
Output Voltage Noise	< 1 V RMS
Output Current	
Negative Polarity	5 Amp
Positive Polarity	1.4 Amp
Output Current Noise	< 10 mA RMS

c. Submerged plant

At the end of the submarine cable a mechanical frame hosts the CTA (Cable Termination Assembly), that splits the power and fibreoptics functions, a MVC (Medium Voltage Converter:10 kV➔ 400 V DC), together with a splitter box providing three electro-optic ROV-mateable connectors (400 V DC and 4 optical fibres) as shown in Figure 6 [3, 4].

A NeMO tower prototype will be connected and powered through the frame to validate the proposed technologies of the NeMO project, and to provide a continuous on-line monitoring of the deep sea site.

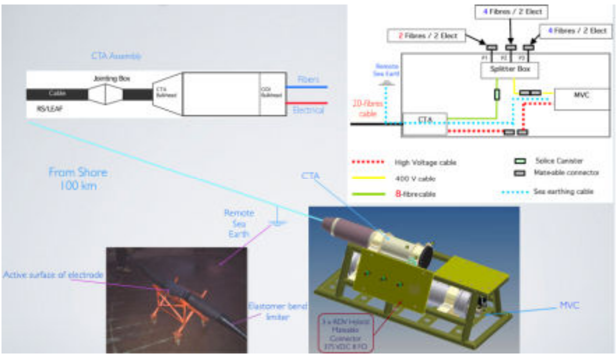

Fig. 6. NeMO Submerged plant: mechanical frame with cable termination, power conversion and power/signal distribution.

d. Deep-sea power conversion

The MVC is based on a design developed by JPL NASA for the NEPTUNE Project [5, 6], and was deployed in the MARS[7] and Neptune Canada [8] projects. It is built from a number of low power sub-converters blocks arranged in a series-parallel configuration, (Fig. 7), to share the load and provide redundancy [9].

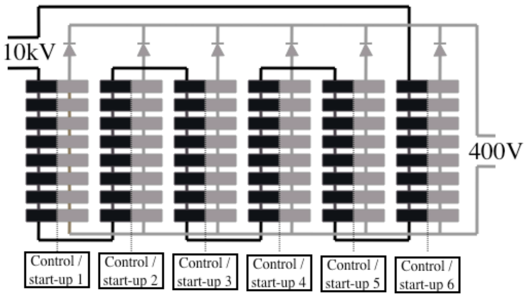

Fig. 7. Medium Voltage Converter: DC/DC Converter layout.

The converter has an input of up to 10 kV DC and output of 375 VDC/28 A. The measured efficiency exceeds 87% at full load. The converter configuration contains 48 Power Converter Building Blocks (PCBB) arranged as matrix of 6 parallel legs with 8 in series in each leg. This arrangement allows for faults within some PCBB's without a failure of the full converter.

The PCBB is a pulse-width modulated switching forward converter with an input of 200 V and an output of 50 V at around 200 W. Each block has four MOSFETs, two working as a primary switch and two on the secondary side as a synchronous rectifier. A block diagram of the circuit is shown in Figure 7. The various transformers are able to withstand continuous 10kV operation in a dielectric fluid.

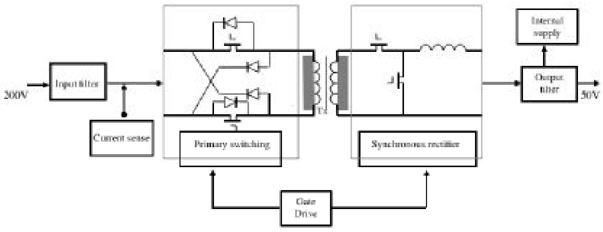

Fig. 7. Medium Voltage Converter: PCBB block diagram.

The entire power converter is housed in a pressure vessel, filled with Fluorinert® dielectric cooling fluid. A parallel stack, containing eight PCBBs on four boards, together with a control board is shown in Figure 8. Its final complete arrangement is shown in Figure 9.

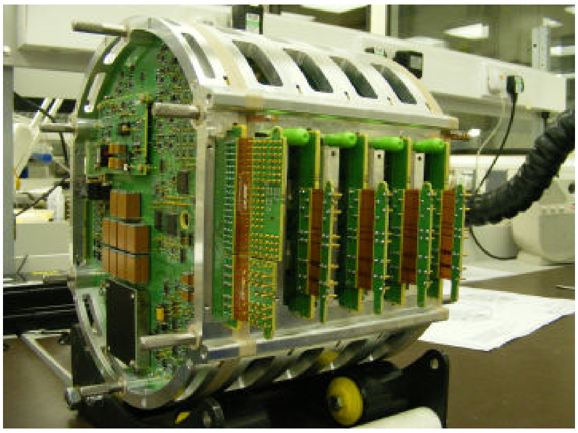

Fig. 8. Medium Voltage Converter: complete parallel 'stack'

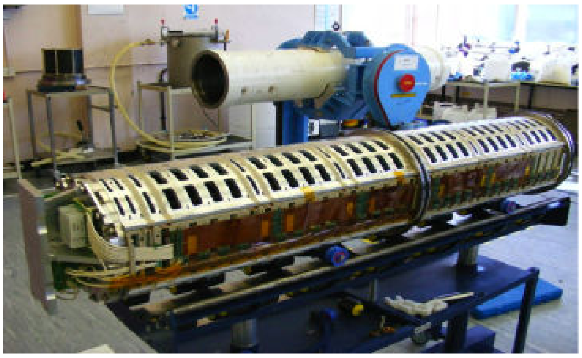

Fig. 9. Medium Voltage Converter: complete assembly.

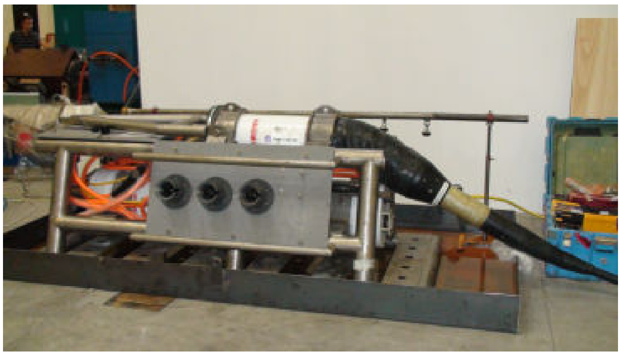

Fig. 10. Final assembly of CTA, MVC and ROV connectors.

V. THE DEEP-SEA CONNECTION SYSTEM

Connectivity issues present particular challenges when there is a practical need for wet-mate connections.

The technical challenges associated with current and planned seabed observatories include:

- *Water Depth:* Down to 4,500 meters
- *High Voltages:* 10,000 VDC
- *High Bandwidth:* The desire to bring real-time science data from individual experiments directly to the shore drives up bandwidth requirements to several Gbits/sec per optical fibre.

During the last two decades the wet-mate connectivity and sea-floor maintainability on the seafloor have benefited from the use of Remotely Operated Vehicles (ROVs). Prior to this time, cabled systems were hard-wired and required the system to be harvested from the seafloor for maintenance or re-configuration.

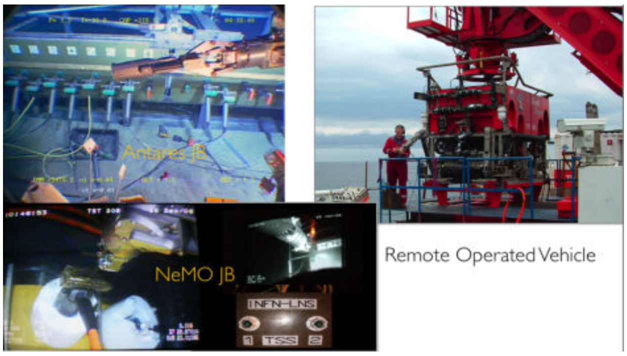

Fig. 11. Wet-mateable ROV connectors in use in ANTARES (top left) and NeMO (bottom).

The enabling technology of wet-mate connectivity is well known throughout the telecommunication, oil & gas industries and the ocean research community. Wet-mate connectivity encompasses not only low-power electrical transmission and all-optical connectors, but also electro-optical hybrid configurations (optics and electrics in one connector) and high-power electrical connectivity. Figure 11 shows examples of this technology in use for NeMO and ANTARES.

VI. THE SEABED POWER DISTRIBUTION

The distribution system represents a network that carries power and data from each DU to and from the main cable. The distribution geometry is under investigation and two possible solutions are under consideration, the Star solution, (Fig. 12) and the Ring solution (Fig. 13). The main difference is in the location of the power conversion system, concentrated in the centre in the first case, or distributed circumferentially in the second. The chosen layout must allow for easy deployment and connection operations as well as for post-installation maintenance operations, which can be difficult and expensive. Special attention must be paid to techniques for maximizing reliability and minimizing underwater operations.

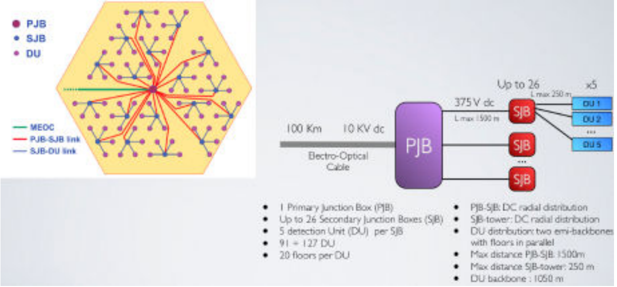

Fig. 12. A possible sea-floor layout using star distribution

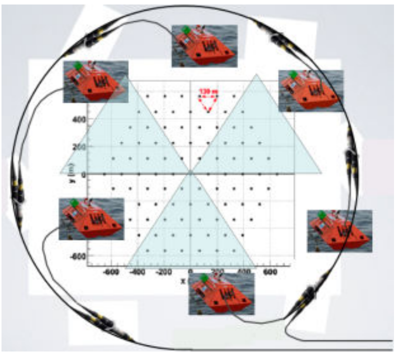

Fig. 13. A possible sea-floor layout using ring distribution

VII. ACKNOWLEDGEMENTS

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