

Strategic Planning and Design Considerations for Effective Deployment of Submarine Power Cable Projects

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Abstract: The deployment of Submarine power cables is a complex and critical task that are essential for transmitting electricity across water bodies, connecting islands, offshore renewable energy sources and providing power supply for oil and gas offshore platforms. This literature review provides a comprehensive guide to the strategic planning and design considerations for effective deployment of these cables. Key consideration includes environmental impact assessments, route planning, advance design consideration, monitoring and maintenance protocols. The paper is structured to cover the essential phases of submarine power cable projects, such as preliminary planning and assessments, emphasizing on the importance of environmental impact assessment and cable route planning. Followed by design consideration section where it explores the material selection for appropriate cable type, mechanical and electrical design challenges. Finally, by leveraging technological advancement, best practices and adhering to the guidelines set forth in IEEE 1120-2004, this paper aims to enhance the reliability and efficiency of submarine power cable systems, ensuring their successful design, implementation and operation.

Keywords: submarine power cable projects, renewable energy, cable route planning.

1. INTRODUCTION

The increasing global demand for renewable energy and the need for robust and reliable power transmission network have prompted significant advancement in the deployment and maintenance of submarine power cables over the past decades. These cables are essential for transporting electricity across water bodies, linking offshore renewable energy sources such as wind and solar farm to onshore facilities, also providing reliable electricity supply for offshore platforms in oil and gas industry [4]. Submarine power cables offer numerous advantages, including the ability to transmit large amount of electricity over long distance across the sea with minimal losses, environmental benefits associated with reduced onshore infrastructure and enhanced energy security through diversified supply routes [11]. However, the design, installation and maintenance of these cables present complex engineering challenges, requiring thorough planning, innovative design solutions and advance installation and maintenance techniques.

The process of deploying submarine power cables involves multiple phases that are critical to the success of the project. Given the harsh and dynamic marine environment in which these cables operate, there are important considerations that required to be carefully managed, such as environmental impact, seabed conditions, mechanical stresses and electrical performance [3]. This paper aims to provide a comprehensive review of the strategies and best practices for the effective planning, design and installation of submarine power cables. By synthesizing current researches, industry standards and best industrial practices to highlight the key elements that contribute to the successful deployment of submarine power cables project.

The IEEE 1120-2004, "IEEE Guide for Planning, Design, installation, and Repair of Submarine Power Cable Systems" serve as a foundation document of this paper providing detailed guidance on various aspects of submarine cable projects. This standard encompasses a wide range of topic, including environmental consideration, cable selection, mechanical and

electrical design, installation methods and maintenance protocols [1]. By adhering to these established guidelines and the key considerations detailed in this paper, project management teams can mitigate risks, optimize performance and ensure long-term reliability of submarine power cable systems.

2. PLANNING AND PRELIMINARY ASSESSMENTS

Effective planning and preliminary assessments are critical to the success of submarine power cables projects. This section details the various main components involved in the planning stage.

2.1 Feasibility Studies

Feasibility studies assess the technical, economic and environmental viability of the project. below is an elaboration on each of these main factors:

Technical Feasibility Analysis

Evaluating whether the project can be implemented using available technology and expertise which include engineering challenges, technological requirements and resource availability.

Economic Feasibility and Cost-Benefit Analysis

Conducting economic analysis and developing rough estimates to determine the financial viability of the project. This include estimating project cost, analyzing potential benefits and developing the net present value (NPV) to compare costs and benefits of the project.

Assessment of Alternative Routes and Technologies

Evaluating alternative routes and technologies helps identify the most efficient and cost-effective solutions for the project.

2.2 Environmental Impact Assessment

Conducting a thorough Environmental Impact Assessment (EIA) is crucial for identifying potential effects on marine ecosystems and developing strategies to mitigate negative impacts. EIA involve detailed studies of marine habitats, water quality and potential disruptions to marine life. These assessments help ensure that the installation of submarine power cables complies with environmental regulations and minimize ecological disturbances [9].

Importance of EIA

EIA are essential for protecting marine biodiversity, ensuring compliance with national and international environmental regulations, engaging with stakeholders and addressing environmental concerns and finally facilitating the permitting and approval process for the next phases of the project.

Methods and best practices for conducting EIA

The first step in developing the EIA is familiarizing with the mandatory standards, regulations and policies. This is essential for several reasons as listed below:

- Compliance: ensure that the project adhere to all applicable legal requirements, avoiding potential legal issues and fines.
- Relevance: local standards and regulations are often tailored to address region-specific environmental concerns, making them highly relevant to the project.
- Streamlined Approvals: facilitates the permitting and approval process by ensuring that all necessary environmental considerations are addressed.
- Global Best Practices: international environmental standards such as ISO 14001 and guidelines from organization like the international Finance Corporation (IFC) provide a framework for best practices in environmental management which ensure the project consider and incorporate globally recognized best practices [7][14].
- Consistency: provides a consistent approach to environmental management across different jurisdictions.
- Credibility: enhance the credibility and acceptance process of the project.

2.3 Regulatory and Permitting Requirements

Navigating regulatory and permitting requirements is a critical aspect of the planning process. This involves early screening and understanding of the legal and regulatory frameworks that govern submarine cable projects. These requirements ensure that projects comply with legal standards, protect environmental and social interests and gain the necessary approvals for implementation. This section provides an overview of the various regulatory frameworks, permitting process and challenges including the importance of compliance with international standards and local regulations.

2.3.1 Overview of Regulatory Frameworks:

Submarine power cables projects are subject to a variety of regulatory frameworks that cover international, national and local levels. Understanding these frameworks is essential for ensuring compliance and smooth project execution.

International conventions and Agreements

- United Nations Convention on the Law of the Sea (UNCLOS) which was adopted in 1982 which provides a legal framework for all marine and maritime activities including the laying of submarine cables.
- International Maritime Organization (IMO) that develops regulations to improve the safety and security of international shipping and to prevent marine pollution from ships. Compliance with IMO guidelines are crucial and relevant to submarine cables projects as it relates to environmental protection and navigational safety [17].

National and Local Regulations

Each country has specific environmental, safety and technical regulations that must be followed. These regulations often include requirements for environmental impact assessments and adherence to national policies and protection laws. For example, in Saudi Arabia the Ministry of Environment, Water and Agriculture (MEWA) and National Center for Environmental Compliance (NCEC) include several Standards, policies and regulations that govern the requirement for environmental assessments for marine projects including submarine power cables [10]. Another example is the United States, where projects must comply with the National Environmental Policy Act (NEPA), which mandates environmental assessments and impact statements for major projects [12].

2.3.2 Permitting process and challenges

The permitting process can be complex and time-consuming which requires careful planning from the early stages of the project. It typically includes several stages as shown below:

Initial application and screening:

This includes the submission of initial documentation by project proponent outlining the project scope, purpose and potential impacts. This is followed by regulatory authorities review to determine if a full environmental impact assessment is required.

Full Environmental Impact Assessment (EIA):

Conducting detailed EIA which involves baseline studies, impact assessments and the development of mitigation measures.

Review and Approval:

This stage involves the submission of a complete EIA report to regulatory authorities, the review by regulatory authorities to assess the adequacy of the report which might include requesting additional information or modifications. Once the EIA report meets all requirements, the necessary permits are issued allowing the project to proceed further.

Permitting Challenges:

The permitting process encounters several challenges due to the requirement for coordination across multiple agencies, facing conflicting regulations and addressing multiple stakeholder concerns. Hence it is necessary to establish stakeholder management plan and risk management plan at early stage of the project to have proactive engagement with key stakeholders to address these challenges and ensure timely approvals to avoid delays in permitting process.

2.4 Route Planning and Selection

Effective route planning and selection are fundamental to the successful installation and operation of submarine power cables. This process involves comprehensive surveys and analysis to identify the optimal paths that minimize environmental disruption, reduce technical challenges and ensure long-term reliability. Hydrographic and geotechnical surveys are one of the important surveys required at early stage of the project. The Hydrographic study includes performing shallow Geophysical

survey, Bathymetric survey and Metocean survey. These surveys provide essential data required for the design and identification of stable and suitable cable routes including, seabed conditions, sub-bottom profile and underwater terrain characteristics [8]. It is important to note that the main criteria for the cable selection process are minimizing distance, avoiding environmental sensitive areas, reducing technical challenges and exposure to natural hazards [3].

2.5 Stakeholders Engagement

Stakeholder engagement is crucial for the successful deployment of submarine power cables projects. Identifying key stakeholders including environmental authorities and government agencies is the first step in this critical process [13]. Engaging and Addressing stakeholders concerns by documenting their input and incorporating feedback, as applicable, into project planning build trust and enhance project outcomes. The stakeholder’s engagement is a continuous process throughout the project life cycle to maintain involvement and ensure that any issues are promptly addressed [16].

2.6 Risk Assessment and Management

This is one of the important processes in the early planning of submarine power cables. Identifying potential risks, such as natural hazards, technical failures and environmental impacts is the first step in safeguarding the project [3] [21]. Employing both qualitative and quantitative risk assessment methodologies allow for a comprehensive evaluation of these risks. Furthermore, developing robust risk management plan including preventive measures, mitigation strategies and contingency plans ensures that project can withstand and respond to potential threats effectively [5].

3. DESIGN CONSIDERATION

The Design phase of submarine power cables projects is crucial for ensuring the system’s reliability, efficiency and longevity. Selecting the appropriate cable type, whether HVAC or HVDC is fundamental decision influenced by transmission distance, power capacity and environmental conditions [6]. Addressing mechanical challenges such as enhancing tensile strength and flexibility is essential for maintaining cable integrity under harsh marine conditions [2]. In this sections, key design considerations are illustrated which are essential for successful submarine power cable projects.

3.1 Cable Selection

Choosing the right type of cable is fundamental to the success of submarine power cable project, the selection process involves evaluating various factors to determine the most suitable cable type for the specific project requirements.

3.1.1 Types of Cables

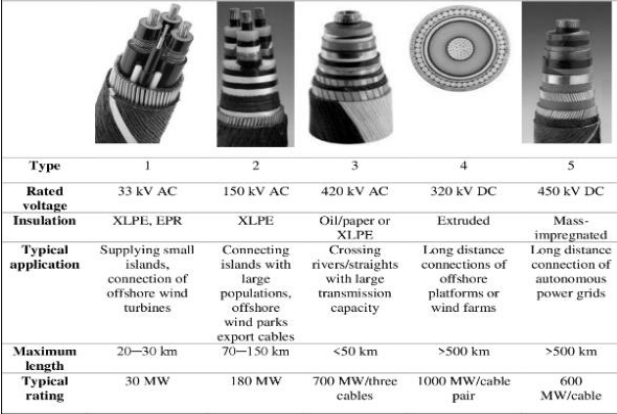
- High Voltage Alternating Current (HVAC)

HVAC cables are commonly used for shorter distances and projects where alternating current is preferable [4]. These cables are simpler in design and easier to install and maintain.

- High Voltage Direct Current (HVDC)

HVDC cables are preferred for longer distances and higher power transmission capacities. They are more efficient for long-distances due to lower energy losses and are increasingly used for international interconnections and wind farms [23].

Figure 1 below shows the five most common type of HVAC and HVDC along with main differences and rating of each type.



| Type | 1 | 2 | 3 | 4 | 5 |
|---------------------|---|--|--|---|--|
| Rated voltage | 33 kV AC | 150 kV AC | 420 kV AC | 320 kV DC | 450 kV DC |
| Insulation | XLPE, EPR | XLPE | Oil/paper or XLPE | Extruded | Mass-impregnated |
| Typical application | Supplying small islands, connection of offshore wind turbines | Connecting islands with large populations, offshore wind parks export cables | Crossing rivers/straights with large transmission capacity | Long distance connections of offshore platforms or wind farms | Long distance connection of autonomous power grids |
| Maximum length | 20–30 km | 70–150 km | <50 km | >500 km | >500 km |
| Typical rating | 30 MW | 180 MW | 700 MW/three cables | 1000 MW/cable pair | 600 MW/cable |

Figure 1: Description of five generic submarine power cable types [34]

3.1.2 Criteria for Cable Selection

Selecting the optimal type of submarine cables involve a comprehensive assessment of several factors including technical, environmental and economic consideration. Below is an overview of the main criteria as outlined in IEEE 1120-2004.

- Transmission Distance:

For distances over 50 Km, HVDC technology becomes more cost-effective and efficient due to lower energy losses compared to HVAC [9].

- Power Capacity:

For high-capacity applications such as connecting large offshore wind farms to the grid or interconnecting national power grids, HVDC cables provide the necessary capacity and efficiency [4].

- Environmental Conditions:

The marine environment including water depth, temperature, seabed condition, soil properties and marine life impact the cable selection [3]. cables installed in deep water or areas with harsh environmental conditions may require additional armoring and advance materials to ensure durability and longevity. This should be part of the Environmental Impact Assessments (EIA) to help determine the appropriate cable specifications and design features to minimize ecological disruption [3].

- Installation and Maintenance considerations:

The ease of installation and maintenance is an important criterion for cable selection. Factors such as topography, presence of obstacles and availability of specialized installation vessels and equipment must be considered [8].

- Regulatory and Compliance Requirements: Compliance with international and local authorities' standards and regulations is essential as they often dictate specific technical and environmental standards that must be met. This is important to avoid legal issues and delays in required approvals and permitting process.

- Cost Consideration:

Overall project cost estimations are required at certain project phase with different accuracy. This is crucial factor in cable selection as it provides the most economical viable option.

3.2 Mechanical and Electrical Design:

The mechanical and electrical design of submarine power cables involves addressing various challenges to ensure durability, reliability and performance under harsh marine conditions. The IEEE 1120-2004 standard provides guidelines for overcoming these challenges and ensuring the cables are designed to withstand the harsh underwater environment. Below is an overview of some of the challenges and proposed solutions.

3.2.1 Mechanical Design Challenges and Solutions

The mechanical design of submarine power cables is critical for ensuring their structural integrity, performance and operational reliability throughout their lifespan. During installation and operation, submarine cables are subject to significant tensile forces resulted from the weight of the cable itself, the drag from currents and the tension applied during laying operations [3]. To enhance tensile strength and ensure durability, cables are often reinforced with high strength materials such as steel wire armoring [20]. In addition, it is important to ensure proper cable handling procedures during installation which can prevent damage and ensure desired performance [1].

Submarine power cables must also be flexible enough to accommodate movement caused by currents, waves and tidal forces. Continuous flexing and bending could damage the cables and cause breaking. The flexibility can be achieved by using specially designed insulation and sheathing materials that maintain their integrity under frequent bending [1]. Materials such as ethylene propylene rubber (EPR) and cross-linked polyethylene (XLPE) are commonly used due to their excellent flexibility and mechanical properties [3].

Moreover, submarine cables are exposed to potential mechanical abrasion and impact from marine activities such as fishing, anchoring and contact with underwater structures. If this occurs, it could damage the cable outer sheathing and lead to water ingress and electrical faults [2]. To protect against abrasion, cables are often equipped with additional armoring layers made of steel wires or other durable materials [1]. Burial below seabed is another effective method used to protect cables from mechanical damages, in addition to the use of advance coating and protective jackets that can improve cable's resistance to harsh underwater environmental conditions [2].

3.2.2 Electrical Design Challenges and Solutions

The electrical design of submarine power cables focuses on ensuring efficient and reliable power transmission. Effective insulation is one of the main aspects of electrical design that prevent electrical faults and ensuring efficient power transmission [24]. High-quality insulating materials such as XLPE and EPR are commonly used because of their excellent electrical insulation, mechanical strengths and resistance to water and chemical ingress [3]. The insulation is typically applied in multiple layers to provide redundancy and enhance reliability which ensure the cables can withstand high voltages and challenging environmental conditions [4].

The choice of conductor material also plays major role in the electrical performance of submarine power cables. Copper and aluminum are the primary materials used for conductors due to their excellent electrical conductivity. Copper has superior conductivity and mechanical strength which make it ideal for high-capacity and long-distance application. Although aluminum is less conductive compared to copper, it is lighter and more cost-effective which make it suitable for application where weight is a critical factor. The conductors are often stranded or layered to improve flexibility and mechanical properties to suit the marine environmental conditions [3].

Proper thermal management is essential to prevent overheating and ensure cables operate within safe temperature limits. Overheating is major issue in all power cables as it can degrade insulation materials and lead to electrical faults. This can be mitigated by designing the cables for adequate heat dissipation which involve selecting materials with high thermal conductivity and optimizing the cable cross-sectional area [8]. It is also important to consider thermal modeling and simulation during the design phase to predict temperature profiles and optimize cable's thermal management [8].

Managing voltage stress is another challenge for submarine power cables to prevent partial discharge that could degrade cable's insulation system. Stress control layers and tapes are applied at the conductor and insulation interfaces to manage electric field distribution and reduce stress concentration, these materials are designed to smooth out electric field gradients and prevent localized electrical breakdown [4]

3.3 Redundancy and Repair Strategies

Considering redundancy and effective repair strategies are crucial aspect during the initial design phase of submarine cable projects. Redundancy is important to maintain power supply continuity, system reliability and mitigate risks associated with cable failures situations. This is done by deploying multiple parallel cables along different routes to provide alternative path for electricity flow in case one cable fails [4]. However, it is important to perform cost-benefits analysis to assess the associated cost implication due to considering redundancy routes and made an informed decision at early stages of the project.

Effective repair strategies and quick response repair plan are vital to minimize the downtime of submarine power cables and reduce the impact on power supply. These plans need to be developed during the design phase of the project to ensure proper implementation, resource availability and cost requirements. Examples of rapid repair and maintenance strategies include utilizing Remotely Operated Vessels, specialized tools, advance jointing and termination techniques, and modular jointing kits [3].

4. TECHNOLOGICAL ADVANCEMENTS AND FUTURE TRENDS

The continuous evolution of technology is positively impacting the advancement in the design, installation and maintenance of submarine power cables. These innovations are enhancing the efficiency, reliability and sustainability of power transmission across marine environment [33]. Below are some of the latest innovations:

4.1 Advance Materials and Protection

Recent development in materials science have led to the development of more robust and efficient cable materials that resulted in enhancing performance and reliability. Innovations such as high-strength polymers, advance insulation materials and corrosion-resistance coatings improve the durability and reliability of submarine power cables [6]. Cable armouring techniques such as double armouring with galvanized steel wires increase cable protection against physical damage from anchoring and fishing activities [18]. As illustrated in Figure 2, the general layout of typical HVDC submarine power cable consist of main conductor in the cable core. This is followed by an insulation system such as extruded material. Then the water barrier that are usually consist of lead and plastic, followed by armouring and finally outer serving sheath.

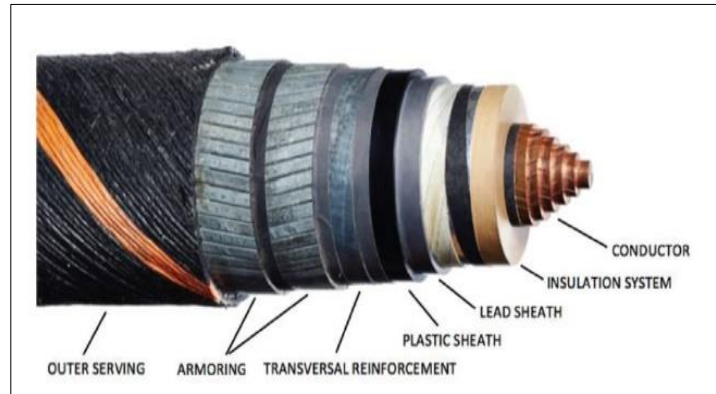


Figure 2: General Layout of typical Submarine HVDC Cable [18]

4.2 Hybrid Cables

The combination of power transmission and data communication (Hybrid Cables) represent significant technological advancement in the submarine cable industry. This approach is used to transmit both power and data via single infrastructure which in turn increase efficiency, reduce complexity associated with managing separate cables and most importantly reduce installation cost [25][22].

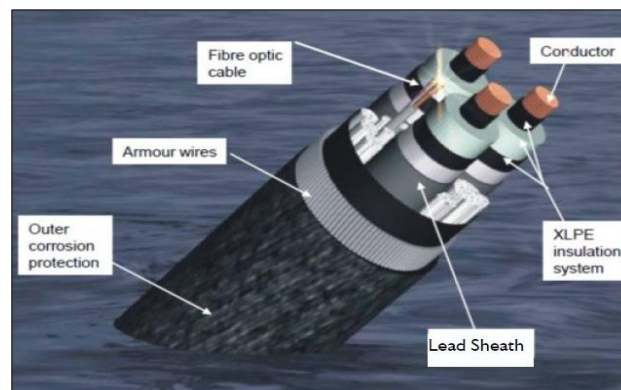


Figure 3: Typical 3 phase HVAC hybrid submarine power cable [19]

4.3 Self-Healing Cable Design

One of the most promising technical advancements in the field of submarine power cables is the development of self-healing mechanism. These are cables engineered with materials that possess the ability to autonomously repair damage. This is achieved by integrating microcapsules containing healing agents within the cable's insulation layers so that when cables experience a damage or crack, the microcapsules rupture and release the healing agent that chemically react to form new bond and seal the damaged area [32] [31].

4.4 Smart Monitoring Systems

The integration of advance sensors and communication technologies into submarine power cables allows for achieving real-time monitoring. The main advantage of real-time monitoring is the ability to detect potential faults early and enable proactive maintenance which enhance the overall reliability of the power transmission system [28].

The application of artificial intelligent (AI) and machine learning (ML) to analyze real-time data has seen significant advancement in recent years. These technologies enhance predictive maintenance tools which enable the prediction of issues before they occur. This proactive approach minimize downtime and extend the lifetime of submarine power cables by allowing timely intervention and maintenance [4] [15].

4.5 Underwater Drone Technology

Underwater drones consist of remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) have revolutionized the installation, inspection and maintenance of submarine cables [26][33]. These drones are equipped with advanced imaging and sensing capabilities that enable precise and efficient operation in deep sea environment which

eliminate the need for human divers [30]. ROVs and AUVs can perform variety of tasks including detailed visual inspections, sediment analysis and real-time monitoring of cable integrity [27][28]. Furthermore, the integration of AI and ML in these drones further enhance their capabilities allowing for autonomous navigation and increase efficiency for real-time data processing [29].

5. CONCLUSION

In conclusion, the strategic planning and effective design considerations explored in this paper plays a major role in the success of submarine power cables projects. Thorough feasibility studies, comprehensive environmental impact assessments form the foundation of responsible and successful project initiation. There are several effective design considerations that are crucial to be explored during the early phase of the project such as material selection criteria, complex mechanical and electrical design challenges. Adopting up to date technical advancement and innovations drives efficiency and sustainability in submarine power transmission systems. These broad overview and considerations not only address current issues and limitation but also pave the way for future enhancement in reliability, performance and aligning with global environmental goals.

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