ELSEVIER
Production And
Hosting By Elsevier
On Behalf Of KeAi

KeAi

Full−length article

Technical and economic demands of HVDC submarine cable technology for Global Energy Interconnection

Xiaoling Zhao[1], Yao Liu[1*], Jiawei Wu [1], Jinyu Xiao[1], Jinming Hou[1], Jinghui Gao[2], Lisheng Zhong[2]

1. Global Energy Interconnection Development and Cooperation Organization, No. 8 Xuanwumennei Street, Beijing 100031, P.R. China

2. State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, P.R. China

Scan for more details

Abstract: Power transmission across the sea is an important part of global energy interconnection (GEI). To support the construction of GEI and to serve the needs of future clean energy trans-sea transportation and offshore wind power development, this study a) analyzes the requirements of the GEI backbone network pertaining to direct current (DC) submarine cable technology, and b) defines the key technical and economic indices of ultrahigh-voltage direct current (UHVDC) submarine cable based on theoretical computations. The research is based on the thermoelectric coupling model and the finite element method. It is shown that the dielectric strength of the insulating materials of the ±800 kV~±1100 kV/ 4000 MW~12000 MW UHVDC submarine cable (extrusion insulation) should be not less than 43~65 kV/mm, while the heat resistance is not less than 110 °C. As the cost of submarine cable is 5~10 times higher than that of the overhead line, the project investment need to be decreased to a level within the economical carrying capacity to guarantee extensive applicability of the HVDC submarine cable technology.

Keywords: UHVDC submarine cable, GEI, Technical index, Economic index.

1 Introduction

Global Energy Interconnection (GEI) provides the infrastructure foundation for large-scale exploitation, global allocation, and complementary and efficient utilization of various clean energy resources at a worldwide scale [1, 2] in which the direct current (DC) submarine cable has an indispensable part for the interconnection of clean energy bases and load power system centers across the sea [3]. Additionally, submarine cables is the only way for the transmission of offshore wind power generated far away from the land back to the land [4].

The highest technical level of submarine project is

applied in the Western Link with a capacity of 2200 MW and a voltage of ±600 kV, transferring renewable energy from Scotland to load centers in Wales and England. However, the transmission distance and capacity cannot satisfy the future demand of the GEI and other large-scale offshore wind power explorations [5, 6]. For example, there are approximately 30 overseas transmission channels proposed in the GEI backbone grid, 50% of which have capacities > 8000 MW. Additionally, the longest planed project planned spans a distance > 2000 km, while the line loss for the extra high voltage (EHV) is too large for that length.

The development of UHV DC submarine cable technology is proposed as the solution that has the capability to transmit large capacities to distant locations. Additionally, given that the engineering cost per capacity decreases with increasing voltage [7], the construction of the UHV DC submarine cable project will reduce the cost of electricity transmission across the sea.

The present study summarizes the demand for overseas power transmission in the GEI backbone grid and proposes the target for the DC submarine cable development. To realize the UHV technology, some key technologies must be overcome, including the design of the structure, and material and processing techniques. Among these technologies, the choice and type of the insulation material is the most critical. In this case, we constructed a multiphasic mode and analyzed the dielectric and thermal index for the UHV DC cable. To promote the widespread application of the DC submarine cable, the cost of the UHV DC submarine cable must be acceptable by the investor and decision-making parties in most counties around the world. Therefore, we calculated the objective cost of the submarine cable project per length according to the difference between the feed-in tariff of clean energy bases and the purchasing electricity price of load centers in the proposed projects in GEI.

2 GEI demand

Offshore clean energy transportation and grid cross-sea interconnections will be the main application scenarios of HVDC submarine cables in the future [8]. It is estimated that by 2050, a) there will be a worldwide market capacity ~160 GW for a total span of 10,000 km, and b) more than 50% of the demand will be UHV-grade DC power transmission with a capacity exceeding 8000 MW [3].

2.1 Asia

Asia is the world's largest power load center and has abundant renewable energy resources. In addition to the connection of the major load centers and the transfer of renewable energy within the continent, the proposed Asian Energy Interconnection also receives clean energy from large energy bases located in various continents through a submarine cable network.

The main submarine transmission channels include the Northeast Asia regional channels, and the Middle East–South–Asia and Europe–South–Asia interconnections. The total transmission distance of the submarine cable is 10,000 km, while the total capacity reaches 120 GW, whereby the proportion of the UHV projects reaches 45%.

For example, the West Asia is a region with a large concentration of solar energy resources in the world. Its maximum solar energy exploration capacity is ~100 trillion kWh/year. The surplus of electricity in West Asia is expected to be 20 million KW in 2035 and 100 million KW in 2050, respectively. To alleviate the imbalance between power supply and demand, the GEI backbone network plans the Oman–India transmission channel with a total length of 2300 km, of which the Oman–India section is 1000 km across the sea, while the maximum depth is 3500 m.

Fig. 1   Pathway and depth of submarine transmission line between Oman and India

2.2 Europe

As one of the essential power load centers, Europe is vigorously pursuing policies and concepts to reduce the scale of fossil energy and nuclear power utilization to increase the proportion of renewable energy utilization. It is a pioneer in the implementation of energy reform. The European Interconnected Power Grid aims to build a strong, ubiquitous European smart grid to ensure efficient access to renewable energy, such as the Arctic wind power, North Sea wind power, Southern European solar energy, and North African solar energy, and to connect with various types of regulated energy types, such as the Nordic hydropower.

In combination with the development and transportation of renewable energy, especially for offshore wind power,

the submarine cable interconnection backbone channels that are interconnected by the European transnational continents include the Nordic regional, Nordic–European, and the European–African interconnections. The total distance of the submarine cable is 9000 km, the total capacity is 120 GW, and the proportion of UHV submarine cable engineering is 69%.

Greenland is an important Arctic wind power development base. The Greenland–Iceland–UK transmission channel included in the GEI is an important way for the transportation of Greenland's wind power resources to be transported to the UK and the European continent. The length of the Iceland–UK section is 830 km. The maximum depth at 170 km from the UK is 1100 m.
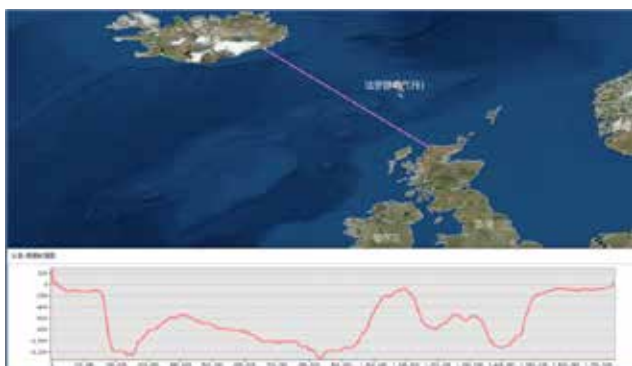

Fig. 2   Pathway and depth of submarine transmission line between Iceland and UK

2.3 North America

North America's middle region and west wind power base, southwest solar power base and Canada hydropower base are connected with the load centers of the west and east by North American power grid. The east load center receives Arctic wind power from Greenland and the wes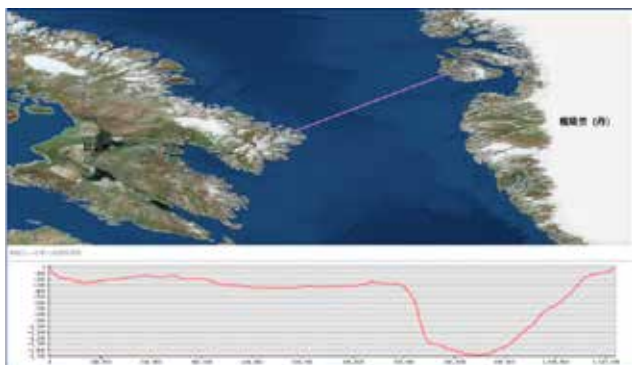t interconnects Asian grid from Alaska, achieving the large-range distribution and high efficient use of renewable energy resources both intercontinental and transcontinental. The main channels of the submarine cable network for North American trans-continental grid interconnection are: Greenland arctic wind power access channel, North America-Asia interconnection channel and North America- South America interconnection channel. The total distance of submarine cable transportation is 5000 km and the total capacity 40 GW, all of which are UHV submarine cable projects.

Greenland arctic wind power access channel has a total length of 1000 km. The maximum depth is 1457 m, 140 km away from the coast of Canada.

2.4 Africa

The proposed African interconnected power grid intends to realize the joint operation of North Africa's solar power and wind power bases with central African hydropower and the Southern African solar power bases to meet the power consumption needs of the entire continent. These interconnections will form a new pattern of electricity transmission from the north to the south and from east to west, with the connection with European and Asian grids. The channels of submarine cable backbone in Africa include the East–Africa–West–Africa Channel and the Africa–European Interconnected Channel. The total length is 4000 km, while the total capacity is 50 GW. The proportion of the UHV submarine cable engineering reaches 40%.

The North Africa region is rich in solar and wind power resources, and can effectively compensate for the power shortage in the energy transformation process in Europe. The Algeria–France–Germany ±800 kV three-terminal DC project is an important channel for the transportation of clean energy from North Africa to Europe. The length of the line is approximately 2400 km. The Lyon–Walgra section is 840 km long across the sea and 2731 m deep at a location 440 km away from France.
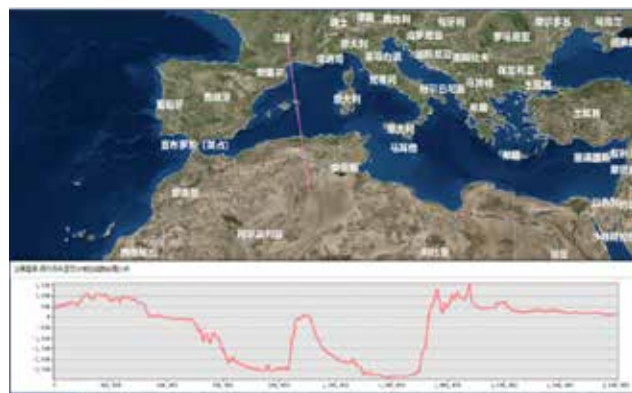

Fig. 3   Oversea power transmission route and sea depth of Greenland-Canada section

Fig. 4   Pathway and depth of submarine line between Lyon, France, and Walgra in Algeria

2.5 Demand analysis

According to the proposed GEI backbone grid, by 2050, there will be a market capacity of 260 GW and total submarine cable length of 23,000 km worldwide. More than 50% of the transmission channels will have transmission capacities > 8000 MW. Given that the largest capacity of a ±700 kV cable is only 3400 MW, the voltage for the capacity of 8000 MW will be at least ±800 kV.

In terms of economy, the current total cost of the ±200~600 kV bipolar UHV DC submarine cable is in the range of $1.0~2.6 million/km that is 5~10 times higher than that of overhead lines. Additionally, the cost per unit capacity of this type of cable declines as the voltage and capacity increase.

Therefore, the UHV DC submarine cable will be more economical than the EHV DC submarine cable, and has the ability to transmit a larger capacity of power to more distant load centers that meets the construction needs of the GEI.

3 Technical Index

To realize the UHV DC submarine cable, the key challenge is the improvement of dielectric and thermal characteristics of insulation materials. We constructed a multiphysics coupling model based on electromagnetics and thermodynamics theories. The multiphysics coupling simulation software COMSOL Mutiphysics was used to establish a two-dimensional simulation model of the UHV submarine cable based on finite element analyses. Accordingly, the electric and thermal fields were simulated during the stable operation of the submarine cable. Extreme electric fields and temperatures were obtained according to the field distribution, and the technical target of the UHV large-capacity DC submarine cable was thus proposed [9-15].

3.1 Coupling theory of electric and thermal fields

(1) Electric field theory

In the finite element analysis of a constant electric field (electrostatic field), the electric potential ϕ is usually used as a solution target [16-23]. In a homogeneous medium, the potential satisfies the Poisson equation or the Laplace equation:

$$\nabla^2 \phi = \rho / \varepsilon \qquad (1)$$

or

$$\nabla^2 \phi = 0 \qquad (2)$$

where ϕ is the electric field, ρ is the charge density, and ε is the dielectric constant.

(2) Thermal field theory

Any point in space corresponds to a unique temperature value. The temperature set of all the points in the selected area is called the temperature distribution of the area [24]. The temperature value of a point in a certain area is a function of space, and is expressed as,

$$T = f(x, y, z, t) \qquad (3)$$

where z, y, and z, are the spatial rectangular coordinates, and t is time.

The present model is used to study the steady-state temperature field of a single-core submarine cable, and is constructed as a two-dimensional model. Therefore, the variables in the temperature function include the two-dimensional coordinates x and y, but exclude the coordinate z and the time term t. This function is expressed as

$$T = f(x, y) \qquad (4)$$

The Fourier law of heat conduction can be used to solve the one-dimensional heat conduction problem. In the two-dimensional model, to reflect the law of heat variation with spatial position, a more general heat conduction equation is needed. According to the law of conservation of energy, the heat transfer equation in any region at any time can be obtained as follows,

$$\frac{\lambda_x (\partial^2 T)}{(\partial x^2)} + \frac{\lambda_y (\partial^2 T)}{(\partial y^2)} + Q_v = 0 \qquad (5)$$

where λ_x and λ_y are the thermal conductivity factors along the directions x and y, respectively, and Q_v is the thermal source per unit space.

Inside the heat source that is composed of (among others) insulation, shielding, current losses occur and eddy currents are generated. It can be considered that the material is an isotropic homogeneous medium. The thermal conductivity coefficient λ in the convertible region can be unified, and the heat exchange equation is thus obtained as,

$$\frac{(\partial^2 T)}{(\partial x^2)} + \frac{(\partial^2 T)}{(\partial y^2)} + \frac{Q_v}{\lambda} = 0 \qquad (6)$$

In the part without heat source, such as the conductor shield and the outer sheath part, the generated loss can be neglected. Thus, the equation of the steady-state temperature field can be simplified to,

$$\frac{(\partial^2 T)}{(\partial x^2)} + \frac{(\partial^2 T)}{(\partial y^2)} = 0 \qquad (7)$$

3.2 Boundary conditions

(1) Structure and electrical parameters

At present, the maximum cross-sectional area of the submarine cable that can be produced by the three-

layer extruder is approximately 21000 mm² (diameter 165 mm), and the maximum cross-sectional area of the conductor produced by the conductor stranding machine is approximately 3500 mm². Considering the technical improvement in the future, the maximum cross-sectional area of the three-layer extrusion of the submarine cable is considered to be 23000 mm² (diameter 170 mm). For ±800 kV cable, the maximum cross-sectional area of the conductor is 4000 mm², and the shielding layer is calculated to be approximately 2 mm. It can be inferred that the thickness of the insulating layer is approximately 45 mm at most. For a ±1100 kV cable, the cross-sectional area of 4000 mm² cannot meet the thermal requirements; correspondingly, the maximum cross-sectional area of the conductor is set at 4500 mm². The shielding layer is calculated to be approximately 2 mm, and the thickness of the insulating layer can be estimated to be approximately 43 mm. According to the technical requirements of ±800 kV/4000–8000 MW and ±1100 kV/12,000 MW, the conductor needs to generate currents in the range of 2500–5454 A. Considering the overload capacity of 20%, the maximum flow capacity of the conductor needs to reach 3000–6545 A.

(2) Temperature

The conductor resistance is increased considerably at high temperatures and high-intensity currents. This leads to large line-losses and low economic efficiency. At the same time, high temperatures cause the local electric field to be reversed in the insulating layer that easily leads to breakdown. Therefore, it is necessary to limit the maximum operating temperature of the cable. At present, the maximum long-term working temperatures of XLPE, MI, and MI-PPLP submarine cable are in the range of 70–85 °C, while that of P-laser submarine cable in the laboratory can reach 90 °C. Taking into account the optimization and advancement of the insulation material in the future, the thermal resistance should not exceed 110 °C.

Table 1 Boundary conditions

Type	Parameter	Boundary condition	
		±800 kV	±1100 kV
Structure	Conductor area s	$s \leqslant 4000$ mm²	$s \leqslant 4500$ mm²
	Insulation thickness d	$d \leqslant 45$ mm	$d \leqslant 43$ mm
Current	I at 1.0 pu	2500 A (4000 MW), (5000 A) 8000 MW	5454 A (12000 MW)
	I at 1.2 pu	3000 A (4000 MW), 6000 A (8000 MW)	6545 A (12000 MW)
Working Temperature	T	$T \leqslant 110$ °C	

continue

| Type	Parameter	Boundary condition	
		±800 kV	±1100 kV
Laying condition	In water	Cable gap 50 m, outer temperature 30 °C, thermal conductivity factor 400 W/(m²·K)	
	Laying under water	Cable gap 50 m, outer temperature 4 °C, thermal conductivity factor 1 W/(m²·K)	
	Laying onshore	Cable gap 50 m, outer temperature 25 °C, thermal conductivity factor 1 W/(m²·K)	

3.3 Simulation case

We consider the simulation case of the technical index for ±800 kV/4000 MW DC submarine cable as an example.

As mentioned above, the cross-sectional area of the conductor is no more than 4000 mm² and the thickness of the insulation layer is 45 mm. The calculation is applied in the case when the cables are operated at the rated power and subject to the three laying conditions, namely, in the seawater, seabed, and landing sections. The temperature and electric field distributions of the cable laid in seawater are shown in Fig. 5. The results show that the long-
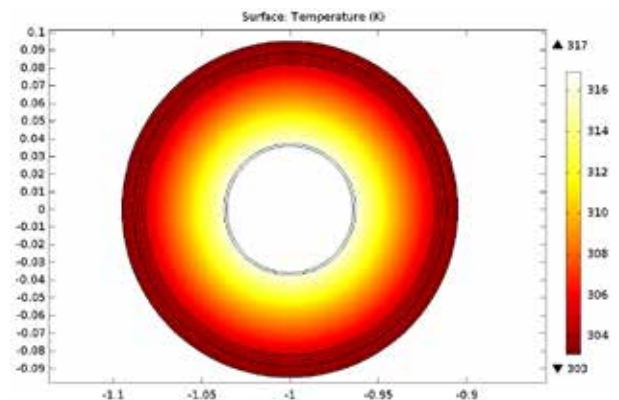
(a) Temperature
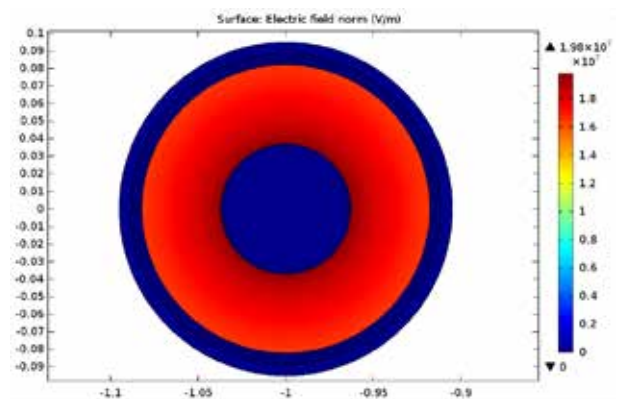
(b) Electric field

Fig. 5 Operating characteristics of cable laid in seawater

term voltage of the insulation needs to reach 19.8 kV/mm, 19.3 kV/mm, and 19.7 kV/mm, respectively, while the highest temperatures need to reach 44 °C, 32 °C, and 46 °C respectively, at these three conditions. The voltage withstanding level of the insulation needs to reach 18.6 kV/mm, 18.2 kV/mm, and 18.6 kV/mm, and the highest temperatures need to reach 57 °C, 48 °C, and 75 °C, respectively, during overload operations at 1.2 pu.

It is clear that for a ±800 kV/4000 MW DC submarine cable, the tolerance voltage of the insulating material should be at least 20 kV/mm, while the thermal resistance should be at least 48 °C in the sea and 75 °C in the landing segment. As the extreme insulation and thermal performances of solid insulation material P-laser are respectively 30 kV/mm and 90 °C [9], the solid extruded insulation materials meet the technical requirements of ±800 kV and 4000 MW for DC submarine cables.

3.4 Results and analyses

For a ±800 kV/4000 MW DC submarine cable, the withstand voltage of the insulating material should be at least 20 kV/mm, while the thermal resistance should be at least 48 °C in the sea and 75 °C in the landing segment. As the extreme insulation and thermal performances of the solid insulation material P-laser are respectively 30 kV/mm and 90 °C, the solid extruded insulation materials meet the technical requirements of the DC submarine cables of ±800 kV and 4000 MW.

For a ±800 kV/8000 MW DC submarine cable, the tolerance electric field intensity of the insulating material should be at least 43 kV/mm, and the heat resistance 110 °C. Compared with the best performance of the current insulation materials, the tolerance electric field intensity characteristics need to be improved by 43% and the heat resistance characteristics by 22.2%.

For a ±1100 kV/12,000 MW DC submarine cable, the tolerance electric field intensity of the insulating material should be at least 65 kV/mm, and the heat resistance cannot be more than 110 °C. Compared with the best performing of the current insulation materials, the tolerance electric field intensity characteristics need to be improved by 117% and the heat resistance characteristics by 22.2%.

4 Economical index

The economical level of DC submarine cable will largely determine the market size and the application prospects. The economic target is studied to ensure that the cost of the transmission project across the sea does not exceed the difference of electricity prices between the beginning and the end of the project based on the expected transmission prices and transmission and transformation equipment costs, in combination with project returns [25].

4.1 Calculation process

(1) Determine the electricity price difference. To calculate the submarine transmission demand of the GEI, we obtain the electricity price difference (floor price - on-grid price) for projects with various voltages and capacities by comparing the on-grid price and the landing price of the submarine cable project.

(2) Set the target internal rate of return. According to the socio-economic development process and its demand for energy consumption, we determine a proper internal rate of return (IRR) for the indicators of major power transmission projects.

(3) Calculate the total investment of a project. For a certain project with a specific voltage grade, transmission capacity and distance, the calculation is based on the target electricity price and the set IRR index, combined with the engineering life cycle, loss, and other engineering parameters, as well as annual depreciation rate, tax, and other cost parameters. The total project investment needs to be calculated, including onshore and offshore transmission investments, and investments in power conversion at both ends.

(4) Determine the total investment of submarine cable. The total investment of the project is subtracted from the cost of the converters/substations and the overhead line to obtain the total investment of submarine cable.

(5) Calculate the economic goals of the submarine cable. According to the total investment and the length of the submarine cable project, the expected economic target per unit length for submarine cable is obtained.

4.2 Computation case

Herein, we consider the computation case of the economic index for the Morocco–Portugal ±500 kV/3000 MW DC power transmission project as an example.

According to a conducted survey, the electricity price difference is 1.14 United States dollars (USD)/kWh wherein the feed-in tariff in Morocco is 3.0 USD/kWh and the grid price in Portugal is 4.14 USD/kWh. The ideal IRR for an engineering project is 15%, but we set it to 8%, which is a relatively good and reasonable value. For a utilization time of 5000 h/year and a 1.79% power loss rate, the total investment of the project is approximately $ 1.2 billion USD. Besides the cost of 60 km overherad transmission on land and two conversation stations on the ends, the 200 km submarine cable investment is approximately 500 million USD. Therefore, the target price of ±500 kV/3000 MW submarine cable in this case is approximately 2.5 USD/km.

4.3 Results and analysis

According to the backbone of GEI and the power grid planning of major continents and regions, the demand for cross-sea transmission is concentrated in Europe, Asia, America, and Africa. The technical demands for prospective

projects for the coming 30 years is ±800 kV/8000 MW, and is estimated to involve ±500 kV/2000 MW, ±500 kV/3000 MW, and ±600 kV/4000 MW UHV projects.

It is estimated that the comprehensive cost for unit lengths of ±500 kV/2000 MW and 3000 MW DC submarine cables should be less than $2.5 million/km, while those for unit lengths of ±600 kV/4000 MW and ±800 kV/8000 MW will be less than less than $3 and $7 million/km, respectively. If there is a project demand of ±800 kV/8000 MW in the short term whose technical level has not yet been reached, the solution of a double circuit in parallel of ±800 kV/4000 MW can be considered, and each single-circuit cost needs to exceed $3.8 million/km.

Table 2   Estimated cost of EHV and UHV submarine cable

Voltage (kV)	Capacity (MW)	Price difference ($/kWh)	Economic targets (single circuit, $ million/km)
±500	2000–3000	0.78–3.53	2.5
±600	4000	1.01–3.43	3.0
±800	4000	1.25–6.32	3.8
±800	8000	1.25–6.32	7.0

5 Conclusions

With the rapid development of large-scale offshore clean energy and the cross-sea interconnection power grids, the demand for transportation capacity, distance, and economy of submarine cable projects has gradually increased. This has led to a continually enhanced impetus for the development of UHV DC submarine cable technology.

(1) There is a substantial market potential for HVDC submarine cables around the world for the next 30 years, especially UHV DC types. According to the GEI plan, the transportation distances of Asia, Europe, North America and Africa will respectively reach 10000 km, 9000 km, 5000 km and 4000 km, while the respective capacities will reach 120 GW, 120 GW, 40 GW and 50 GW, before 2050. Most projects have transmission capacities in the range of 4000~8000 MW, and some have lengths in the range of 2000~3000 km. These characteristics cannot be easily achieved with the current EHV DC submarine cables. Accordingly, there is an urgent need to develop UHV DC submarine cable technology at ⩾ ±800 kV.

(2) To realize the breakthrough of UHV DC submarine cable technology, some key technical index specifications need to be met. Regarding the technical aspects, the characteristics of the insulation material constitute the core difficulties for UHV cables. With multiphysics simulations, it is expected that the voltage resistance of the (extrusion) insulation material of ±800–1100 kV UHV DC submarine cables with capacities in

the range of 4000–12,000 MW should be no less than 43~65 kV/mm, while the heat resistance needs to be>110 °C. The future cross-sectional area of the cable conductor is expected to be in the range of 1250–4500 mm^2.

(3) To realize the worldwide applications of UHV DC submarine cable technology, some key economic indices need to be reached. It is expected that ±500 kV/2000–3000 MW, ±600 kV/4000 MW, and ±800 kV/8000 MW DC submarine cables need to be decreased to approximately $2.50, $3.0, and $7.0 million/km, to ensure comparative market competitiveness with overhead line costs.

Acknowledgements

References

[1] Li J, Jiang S (2018) Global Energy Interconnection: an effective solution to climate challenges. Global Energy Interconnection, 1: 406-408

[2] Liu Z (2015) Global energy internet, China Electric Power Press, Beijing, China

[3] Li J, Song F, Yu X (2018) Backbone plan research on Global Energy Interconnection, Global Energy Interconnection, 1(5): 527-536 (in Chinese)

[4] Xiaoxia W, Ding J, Liu J (2017) Benefit and cost competitiveness analysis of wind and solar power inter-continent transmission under global energy interconnection mode, in IOP Conference Series: Earth & Environmental Science, Volume 52, Sanya, China, November 21-23, 012002

[5] Worzyk T (2009) Submarine power cables: design, installation, repair, environmental aspects, Springer Science & Business Media, Berlin, Heidelberg

[6] Giovanni M, Massimo M. (2013) Extruded cables for high-voltage direct-current transmission: Advances in research and development. Wiley & Sons, UK, 2013

[7] Purvins A, Sereno L, Ardelean M, et al (2018) Submarine power cable between Europe and North America: A techno-economic analysis, Journal of Cleaner Production, 186: 131-145

[8] Zhenya L (2016) Research of global clean energy resource and power grid interconnection, Proceedings of the CSEE, 36: 5103-5110 (in Chinese)

[9] Zhonghua L, Lele L, Huan Z, et al (2016) Simulation study on influencing factors of HVDC cable electric field distribution. Chinese Journal of Electrical Engineering, 36(548 (9)): 251-259 (in Chinese)

[10] Zhengzheng C, Zhao Jiankang Z, Benhong O, et al (2014) Analysis of insulation characteristics and mechanism between dc and ac crosslinked polyethylene cable materials. High voltage technology, 40(9): 2644-2652 (in Chinese)

[11] Sheng C (2018) Analysis and Suggestions on submarine cable fault. Electromechanical information, 21:11-12 (in Chinese)

[12] Xi C (2015) Research status and development of crosslinked polyethylene HVDC cables. Wire & Cable, 02:4-8 (in Chinese)

[13] IEC 60287-1-1 (2006) Electric cables-Calculation of the current rating-Part 1-1: Current rating equations (100 % load factor) and calculation of losses

[14] Linjie Z, Xiaobin Z, Tianwei L, et al (2014) Design and selection of ±160 kV XLPE insulated cable system for multi-terminal VSC HVDC power transmission system. High Voltage Engineering 40(9): 1-9 (in Chinese)

[15] Wenjie M, Wenlin P, Tao C, et al (2017) Structure design of 500 kV dc submarine photoelectric composite cable. Fiber Optics and Cables and their Application Technology 06: 13-18 (in Chinese)

[16] Xinhong Y, Baozhong H, Qingqiang H, et al (2014) Simulation of electrical field distribution of XLPE insulated HVDC cable, Electric Machines & Control, 18: 19-23

[17] Tsuyoshi IGI, Shinya ASAI, Shoji MASHIO et al. (2019) Qualification, installation and commissioning of world's first DC 400 kV XLPE cable system, in Paris: Jicable: A6-1

[18] Ming H, Shuhong X, Jiamnin Z, et al (2014) Design and test of China first ±160 kV DC cable for flexible DC transmission project, In 2014 IEEE China International Conference on Electricity Distribution (CICED)

[19] Yanpeng H, Yun C, Lin Y, et al (2017) Coupled Simulation on Electro-thermal-fluid Multiple Physical Fields of HVDC Submarine Cable. High Voltage Technology 11: 68-76 (in Chinese)

[20] Huang J (2016) Study on electro-thermal coupling and steady-state rating computation of HVDC XLPE cable. Guangzhou, China: South China University of Technology (in Chinese)

[21] Hao Y, Chen Y, Yang L, et al (2017) Study on simplification and equivalence of 3D simulation model of HVDC submarine cables, Southern Power System Technology 11(4): 1-7 (in Chinese)

[22] Chang L, Zheng X, Yaowei X, et al (2016) Simplified finite element algorithm for steady-state load flow of dc cable based on equivalent thermal conductivity. High Voltage Electrical Appliances 52(326 (5)): 12-18 (in Chinese)

[23] Weedy B M, Chu D. (1984) HVDC extruded cables-parameters for determination of stress. IEEE Transactions on Power Apparatus and Systems PAS- 103(3): 662-667

[24] Wang Y, Li G, Wu J, et al (2017) Effect of temperature on space charge detrapping and periodic grounded DC tree in cross-linked polyethylene, IEEE Transactions on Dielectrics & Electrical Insulation 23: 3704-3711

[25] Huanlin W, Bo Q, Pinglang Z(2014) 500 kV submarine cable engineering cost structure and investment level analysis, China Electric Power (Technology Edition) (10). (in Chinese)

Biographies

Xiaoling Zhao received her bachelor's degree from the Wuhan University, Wuhan, in 2013, and her Ph.D. degree from Shanghai Jiao Tong University, Shanghai, in 2018. She is currently working in GEIDCO, Beijing. Her research interests include high-voltage insulation, GIS, and submarine cable technology.

Yao Liu received his bachelor's degree from the North China Electric Power University, Beijing, 2006 and his master's degree from the China Electric Power Research Institute, Beijing, 2009. He is working in GEIDCO, Beijing. His research interests include HVDC transmission, electric system simulations, and new transmission technology.

Jiawei Wu received her Ph.D. degree in Electrical Engineering from Xi'an Jiao Tong University in 2018. She is working in GEIDCO, Beijing. Her research interests include pulse power technology and VSC-HVDC technology.

Jinyu Xiao received her Ph.D. degree in Electrical Engineering from Tsinghua University, in 2005. He is working in GEIDCO, Beijing. His research interests include electrical system planning and new clean energy technologies.

Jinming Hou received his bachelor's degree in Electrical Engineering from the North China Electric Power University in 2002 and her Master's degree in Electrical Engineering from North China Electric Power University in 2006. He is working in GEIDCO, Beijing. His research interests include power system and automation.

Jinghui Gao received his Ph.D. degree in Electrical Engineering from Xi'an Jiao Tong University in 2012. He is working in Xi'an Jiao Tong University, Xi'an. His research interests include functional dielectrics and their applications in cable technology, dielectric and energy storage, and bioelectromagnetic effect.

Lisheng Zhong received the Ph.D. degree in Electrical Engineering from Xi'an Jiao Tong University, in 1997. He is working in Xi'an Jiao Tong University, Xi'an. His research interests include dielectric and electrical insulation, cable technology, and bio-dielectrics.

(Editor　Zhou Zhou)