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Simulation and Experiments on ±100 kV/1 kA DC Superconducting Energy Pipeline for Energy Interconnection

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SUMMARY

China has the necessity of long-distance transmission to overcome uneven geographical distribution of electrical and fuel energy sources and power demands because the energy resources are mainly located in the western and northern regions, while the load centers located in the eastern and south regions. For achieveing the cooperative transmission of different forms of energy, a novel concept of hybrid energy interconnection transmission of superconducting electricity and liquified natural gas (LNG) is proposed to increase the energy transmission density and save manufacturing costs. It has been regarded as a potential form of futural power systems.

DC Superconducting Energy Pipeline (DC SEP) technology integrates DC superconducting cables and LNG pipelines to achieve hybrid transmission of electricity and chemic fuel via sharing a thermal insulating pipeline and refrigeration equipment. It can play an important role in energy interconnection, meeting the common needs of superconducting cables (SCs) and liquefied natural gas (LNG) pipelines at low temperatures.

±100 kV/1 kA DC SEP has been numerically modeled by finite element method (FEM) in this paper, based on its designed structure. It mainly consists of a thermal insulating pipeline with the vacuum layer, two DC superconducting cables with opposite polarity and several LNG pipelines. The electro-magnetic-fluid-temperature coupled multiphysics of DC SEP is realized by simulation .

Simulation results show that, due to the opposite direction of currents in two DC superconducting cables, magnetic field is enhanced spatially between two DC superconducting cables and it is weakened on two sides. Besides, in outlet cross section of DC SEP, the heat transfer field is distributed almost symmetrically with respect to gravity direction. Due to the thermal convection of LN_2, the temperature at the top of DC SEP is higher, and the temperature at the bottom of DC SEP is lower. Meanwhile, LN_2 flows between two DC superconducting cables is the strongest.

Furthermore, a test platform has been designed and constructed, including a DC SEP prototype, a full power test system, and a cooling circulation system. Experiments for hybrid transmission of electricity and fuel have been conducted, such as length test, operating temperature test, LNG transporting test, high voltage insulating test, and full power operating test. The experiment results show that DC SEP prototype has a length of 31.2 m; its operating temperature is 88.4-93.0 K; its LNG flow is 100 L/min; its operating voltages are +100.6 kV/-100.5 kV; its operating currents are +1013 A/-1007A; its total electrical power is 203.1 MW.

The achievement of designing and constructing a ±100 kV/1 kA DC SEP prototype significantly verifies the feasibility of hybrid transmission of superconducting electricity and cryogenic fuel. This technology provides a novel approach to energy interconnection.

KEYWORDS

DC Superconducting Energy Pipeline (SEP); electrical – power; experiment; hybrid – transmission; liquified natural gas (LNG); Liquified Nitrogen (LN_2); multiphysics – field;

I. INTRODUCTION

China has an uneven spatial distribution with abundant energy sources in the northwest areas and huge demand for electricity in the southeast areas. Therefore, it is necessary for China to develop capabilities of transmitting electricity and chemical fuel over long distances. Over the past few decades, China has built some projects for long-distance transmission, such as ultra-high voltage (UHV) transmission lines and compressed natural gas (CNG) pipelines.

With the deveopment of superconductivity and cryogenic technologies in recent years, Chinese National Key R&D Project has proposed a new concept of energy interconnection called the DC superconducting energy pipeline (SEP) in 2018. On the one hand, the critical temperature of BiSrCaCuO (BSCCO) high temperature superconducting (HTS) tapes produced by Japan Sumitomo Corporation has exceeded 100 K. On the other hand, natural gas can be refrigerated below the critical temperature and keep liquified states with some mixture components. Therefore, CNG pipelines can be replaced by liquified natural gas (LNG) pipelines for more energy density. These developments provide the feasibility of DC SEP that combine the superconducting cables (SCs) and the LNG pipelines.

DC SEP is a kind of hybrid transmission of electric power and chemical fuels. It has significant advantages in energy interconnection. For example, it has the zero resistance characteristic of superconductors, with low loss and great economic efficiency.h. Moreover, it has a large energy density and thus occupies a small construction area. Furthermore, it can utilize the facilities of CNG pipelines and share refrigeration stations for superconducting cables and fuel pipelines, thus reducing the construction cost.

At the beginning of the twenty-first century, some researches were conducted on hybrid transmission of electric power and fuels. In 2004, America Electric Power Research Institute proposed a concept of “supercable” at first, which is a superconducting cable cooled by liquified hydrogen (LH_2), regarded as the initial SEP [1]. In 2006, University of Bologna in Italy indicated the hybrid transmission for long-term and long-distance scenarios [2, 3]. In 2008, Japan National Institute for Fusion Science published a conceptual design of a 1000 km. 1 GW superconducting cable cooled by LH_2 [4, 5]. In 2013, Russian Scientific R&D Cable Institute manufactured a SEP prototype with the material of MgB_2 and cooled by LH_2, and then it successfully operated in the operating temperature zone from 20 K to 25 K in experiments [6, 7]. In recent years, China attempts to replace LH_2 with LNG, which is more economical, more accessible and requires less power to refrigerate. In 2019, China manufactured a 10 kV prototype of DC SEP cooled by LNG, which has succeeded to operate in the temperature zone from 85 K to 105 K [8]. In 2020, a general design of ±100 kV DC SEP has been proposed in China [9]. However, existing achievements are not sufficient for the demonstration application of DC SEP, and thus more researches are strongly requested.

According to its designed structure, an operational simulation model of ±100 kV/1 kA DC SEP has been built up in this study based on finite element method (FEM). Afterwards, its multiphysics coupling characteristics have been analyzed based on simulation results. Finally, a 30 m, ±100 kV/1 kA DC SEP prototype has been constructed and demonstrative experiments have been successfully conducted.

II. MULTIPHYSICS COUPLING MODEL

A. GEOGRAPHIC STRUCTURE

The structure parameter of ±100 kV/1 kA DC SEP is listed in Table 1. It is designed to adopt a non-coaxial structure, as shown in Fig. 1. A thermal insulating pipeline is the shell of DC SEP, which consists of several layers including a vacuum layer to reduce heat transfer from outer environment. DC superconducting cables and LNG pipelines are arranged separately in the thermal insulating pipeline. Two poles of DC superconducting cables are arranged on the bottom of the thermal insulating pipeline. One is operating at the voltage of +100 kV and the other is operating at the voltage of -100 kV. Three LNG pipelines are arranged at the top of the thermal insulating pipeline, which are located as an isosceles triangle. Liquified nitrogen (LN_2) is filled as an insulating medium inside the thermal insulating pipeline, into which DC superconducting cables and LNG pipelines are immersed. LN_2 is pressurized and heated to approximately 90 K, which is the operating temperature of LNG.

TABLE 1
STRUCTURE PARAMETERS OF DC SEP

Item	Value	
Thermal isolation pipeline	Inner radius	122.5 mm
	Outer radius	168.5 mm
LNG pipeline	Inner radius	30.15 mm
	Outer radius	36.5 mm
DC superconducting cable	Inner radius	5 mm
	Outer radius	40.25 mm
Operating temperature	85-90 K	

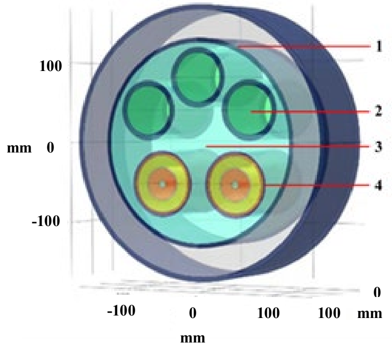


Fig. 1. The 3D structure of DC SEP. (1. the thermal insulating pipeline; 2. LNG pipeline; 3. LN_2; 4. superconducting cable)

The functional structure of a DC superconducting cable applying to DC SEP is shown in Fig. 2. The center is a spiral pipe filled with LN_2. The copper former is the skeleton supporting the superconducting cable, which can also protect the superconducting layer from short circuit faults by sharing current. The superconducting layer is the main component in charge of transmitting electricity. The insulating layer prevents high voltage from damaging other components of DC SEP. The shield layer is a normal conducting layer, which can hinder the electromagnetic interference to another superconducting cable and outer environment. The sheath prevents the superconducting cable from damages.

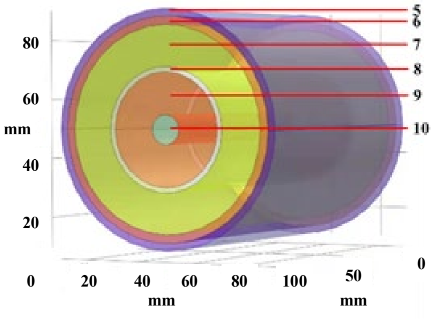


Fig. 2. The 3D structure of a DC superconducting cable. (5. the sheath; 6. the shield layer; 7. the insulating layer; 8. the superconducting layer; 9. the copper former; 10. LN_2)

B. MODELLING METHOD

DC SEP consists of three main components. DC superconducting cables are responsible for transmitting electricity, which generates coupled electric field and magnetic field naturally. LNG pipelines are in charge of transmitting fuel, which is LNG. Besides, the thermal insulating pipeline is filled with LN_2. Both LNG and LN_2 are fluids, which form the fluid field of DC SEP. In addition, these flowing fluids generate frictional heat and contribute to transfer heat by convection.

Characteristics of coupled electric field and magnetic field of DC SEP are modeled by three governing equations.

The first governing equation is the ***E*-*J*** power law. It applies to establishing the functional relationship between the electric field strength ***E*** and the current density ***J*** in a superconductor, expressed as

$$\boldsymbol{E} = \frac{E_0}{J_c} \cdot \left(\frac{J_{norm}}{J_c} \right)^{n\text{-}1} \cdot \boldsymbol{J} \tag{1}$$

where E_0 is the standard electric field criterion, it is assumed as 10^{-4} V/m; J_c is the critical current density of the HTS tape; n is a constant dependent on the nature of HTS materials, and assumed as 21 in this paper; J_{norm} is the modulus of $\boldsymbol{J}$.

The second governing equation is Faraday's law. It applies to establishing the functional relationship between the electric field strength $\boldsymbol{E}$ and the magnetic flux density $\boldsymbol{B}$. Unlike that $\boldsymbol{J}$ only exists in the superconductor, $\boldsymbol{B}$ exists in the whole space. This equation is expressed as

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{2}$$

The third governing equation is Ampere's law. It applies to establishing the functional relationship between the magnetic flux density $\boldsymbol{B}$ and the current density $\boldsymbol{J}$, expressed as

$$\nabla \times \boldsymbol{B} = \mu_0 \cdot \boldsymbol{J} \tag{3}$$

Characteristics of fluid field of DC SEP are modeled by Navier-Stokes equations, regarding a relatively slow fluid as a laminar flow. There are two governing equations for fluid field based on the conservation laws of mass and momentum.

The first governing equation is based on the conservation law of mass, expressed as

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \boldsymbol{v} \right) = 0 \tag{4}$$

where $\boldsymbol{v}$ is the velocity vector of the fluid; ρ is the time-varying density of the fluid.

The second governing equation is based on the conservation law of momentum, expressed as

$$\rho \frac{\partial \boldsymbol{v}}{\partial t} + \rho \left(\boldsymbol{v} \cdot \nabla \right) \boldsymbol{v} = \rho \boldsymbol{g} - \nabla p + \eta \nabla^2 \boldsymbol{v} \tag{5}$$

where $\boldsymbol{g}$ is the gravity acceleration of the earth; p is the pressure of the fluid; η is the dynamic viscosity of the fluid.

Characteristics of temperature filed of DC SEP are modeled by heat balance equations. There are three forms of heat transfer, including heat conduction, heat convection and heat radiation. In low temperature systems, heat radiation can be negligible, so heat conduction and heat convection are mainly taken in consideration.

Heat conduction is a phenomenon that heat flows through adjacent material. The governing equation of heat conduction is expressed as

$$\frac{\partial T}{\partial t} = \frac{k}{\rho C_p} \cdot \nabla^2 T + \frac{q}{\rho C_p} \tag{6}$$

where T is temperature; k is the thermal conductivity of the material; ρ is the density of the material; Cp is the heat capacity at constant pressure of material; q is the heat generating power at the point, such as heat leakage from outer environment.

Heat convection is a phenomenon that fluid flows and carries its temperature to a new position. It occurs only in the fluid region. In the process of flowing, fluid generates heat because of friction. Thus, the heat generated by fluid is equal to the loss of mechanic energy of the fluid, expressed as

$$q_f = -\frac{dE_m}{dt} \tag{7}$$

where q_f is the heat generating power of frictional force; E_m is the mechanism energy of the fluid.

In addition, Joule heat is another type of heat, including AC loss, which is generated by electric field and magnetic field in the superconducting cable. It refers to the phenomenon that the electric field strength E does work on the current density J in the superconducting cable, expressed as

$$q_{SC} = \boldsymbol{E} \cdot \boldsymbol{J} \tag{8}$$

where q_{SC} is the heat generating power in the superconducting cable. However, in steady state, DC current ripple in the superconducting cable is extremely small without fault current impact. Thus, AC loss can be negligible compared to other heat sources.

The temperatures of LNG pipelines inlets are almost fixed by the refrigeration stations. Thus, theses inlets are considered as cold sources for the DC SEP thermal system. They are modeled as boundary conditions in simulation.

III. SIMULATION

The 3D FEM model of ±100 kV/1 kA DC SEP has been established. Its operating parameters are given in Table 2 and its mesh structure is shown in Fig. 3. According to these settings, multiphysics coupling characteristics of DC SEP are simulated.

TABLE 2
OPERATING PARAMETERS OF DC SEP

Item	Value
SEP module length	100 mm
Rated voltage of superconducting cables	±100 kV
Rated current of superconducting cables	±1 kA
LNG flow	0-200 L/min
SEP operating temperature	85-90 K
Heat leakage	0-5 W/m

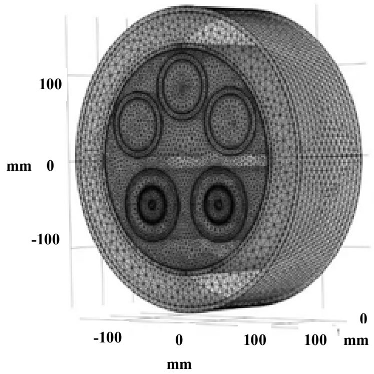


Fig. 3. The 3D mesh structure of DC SEP.

Characteristics of electro-magnetic field on the cross section of DC SEP are shown in Fig. 4. When currents in the two superconducting cables have the same magnitudes of 1 kA but in opposite directions, the magnetic flux density ***B*** between the two superconducting cables is enhanced and flows from bottom to top. However, it is weakened outside the two superconducting cables. The maximum reaches to 0.01 T.

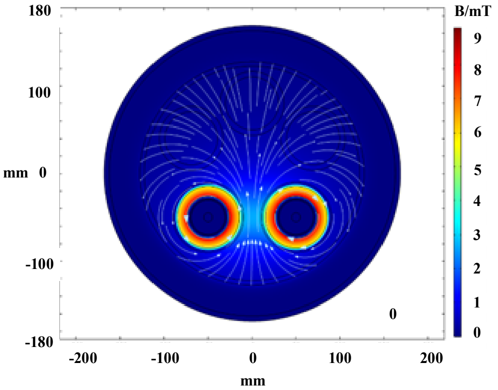
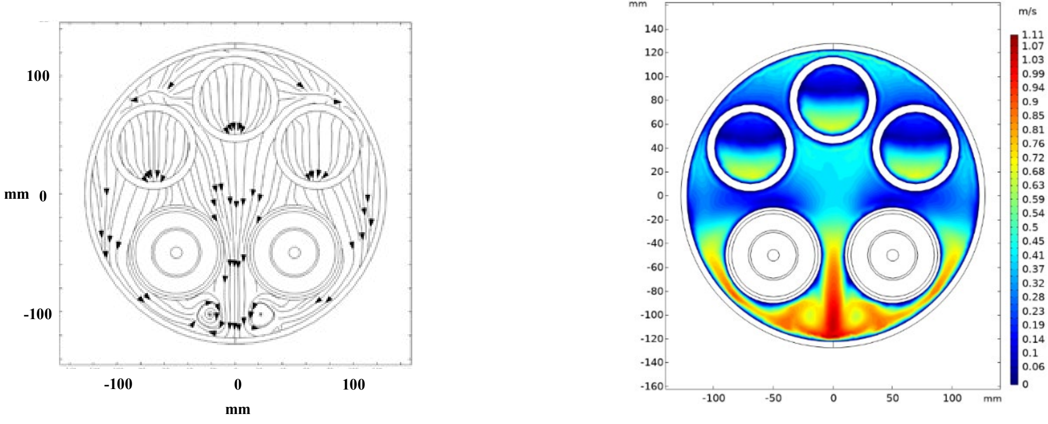


Fig. 4. Characteristics of electro-magnetic field on the cross section of DC SEP.

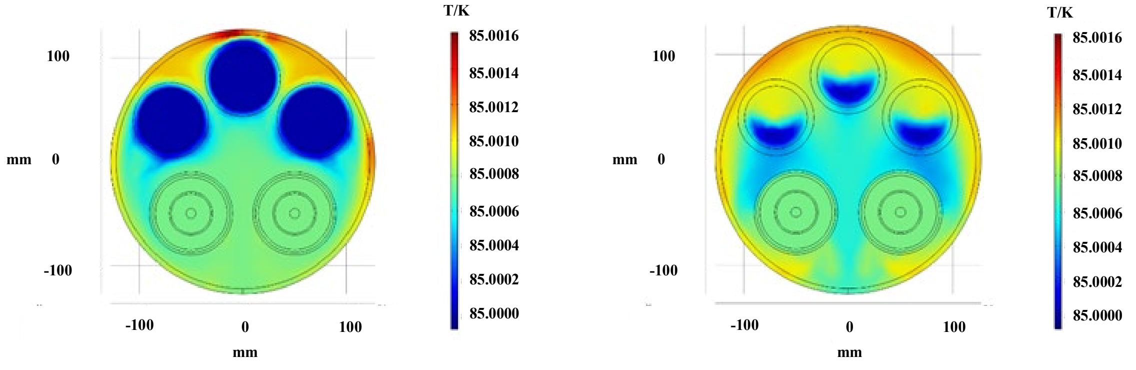
Characteristics of fluid field on the outlet of DC SEP model are shown in Fig. 5. Arrows in the streamline diagram indicate the velocity directions and movement traces of cold fluids in the upright direction. They show that both cold LNG and cold LN_2 generally sink to the bottom in the process of fuel transmission, which is a form of heat convection driven by gravity. Accordingly, hot LNG and LN_2 generally float to the top. Colors in the velocity cloud diagram indicate the speed magnitudes of LNG and LN_2. Due to the acceleration by gravity in the process of sinking, their speedsachieves the maximum at the bottom of LNG pipelines and the thermal insulating pipeline respectively. When LNG flow is 100 L/min and heat leakage is 1 W/m, the maximum speed can reach approximately 1.1 m/s.



(a) (b)

Fig. 5. The diagrams of fluid field on the outlet of DC SEP model. (a) streamline diagram; (b) velocity cloud diagram.

Characteristics of temperature field of DC SEP are shown in Fig. 6. Comparative analysis has been conducted toward temperature fields of the inlet and the outlet of DC SEP. It shows that cold LNG fills up the inlets of LNG pipelines and sinks to the bottom in the outlet. In addition, as for LN_2, high temperature regions are located on the top and near the surface of DC SEP and low temperature regions are located in the middle and bottom. Heat convection of fluids significantly influence temperature field, so the distribution of temperature field is highly consistent with the flow of fluid field in DC SEP.



(a) (b)

Fig. 6. Temperature field of the DC SEP model on the inlet and outlet cross sections. (a) the inlet; (b) the outlet.

IV. EXPERIMENT PLATFORM

A. FULL POWER TEST PLATFORM

A full power test platform has been built up for the experiment of DC SEP prototype, as shown in Fig. 7. As DC SEP has two identical superconducting cables in addition to their opposite electrical polarity, there is a positive circuit and a negative circuit respectively. Each circuit consists of a 1 kA DC current supplier and a 100 kV high voltage source. And the two DC current suppliers have been suspended at the high potential.

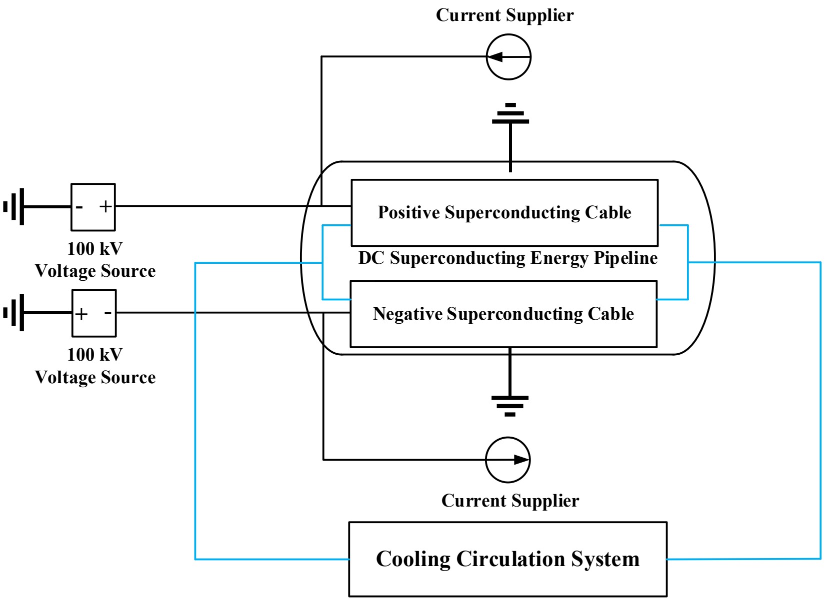


Fig. 7. The scheme of the full power test system of DC SEP.

B. Cooling Circulation System

A cooling circulation system has been established for DC SEP, as shown in Fig. 8. Commonly LNG is a kind of mixture. Most of its composition are methane, and otheres are ethane, propane, and other components. By controlling valves, propane of 110 K is inserted into LNG with a certain proportion. Then mixed LNG is cooled to 85 K. Pressurized LN_2 is injected into the remaining space of SEP and does not flow. Finally, mixed LNG and LN_2 cool the entire DC SEP to the operating temperature of 85-90 K, with refrigerator and pump keeping the circulation of LNG.

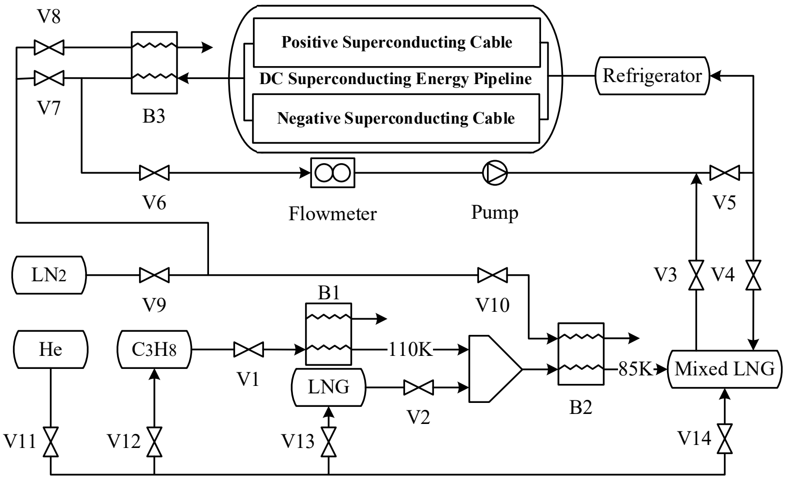


Fig. 8. The cooling system of DC SEP. (He: helium; C_3H_8: propane; V: valve; B1-B3: subcooling box.)

C. Test Site

The DC SEP experimental system has been constructed, as shown in Fig. 9. It includes a 30m, ± 100 kV/1 kA DC SEP prototype, a refrigeration station with transporting pipelines, and the full power test system.

Fig. 9. The photograph of DC SEP test system.

V. EXPERIMENTS

A. LENGTH

A meter counter is used to measure the distance between the high voltage leads at the two ends of the superconducting cable of DC SEP prototype. The result shows that DC SEP prototype has a length of 31.2 m accurately, which meets the construction target of 30 m.

B. OPERATING TEMPERATURE

In the operating temperature test, PT100 platinum resistance thermometers are used to measure the temperatures of the inlet and the outlet of DC SEP prototype. Besides, the refrigerating power of the refrigeration station is slightly reduced for the purpose of testing the performance of DC SEP prototype to keep operating and withstand interference. The result show that the inlet temperature is 88.4 K and the outlet temperature is 93.0 K, with an average of 90.7 K. DC SEP prototype is able to maintain stable operation at this temperature, which verifies its anti-interference ability.

C. LNG FLOW

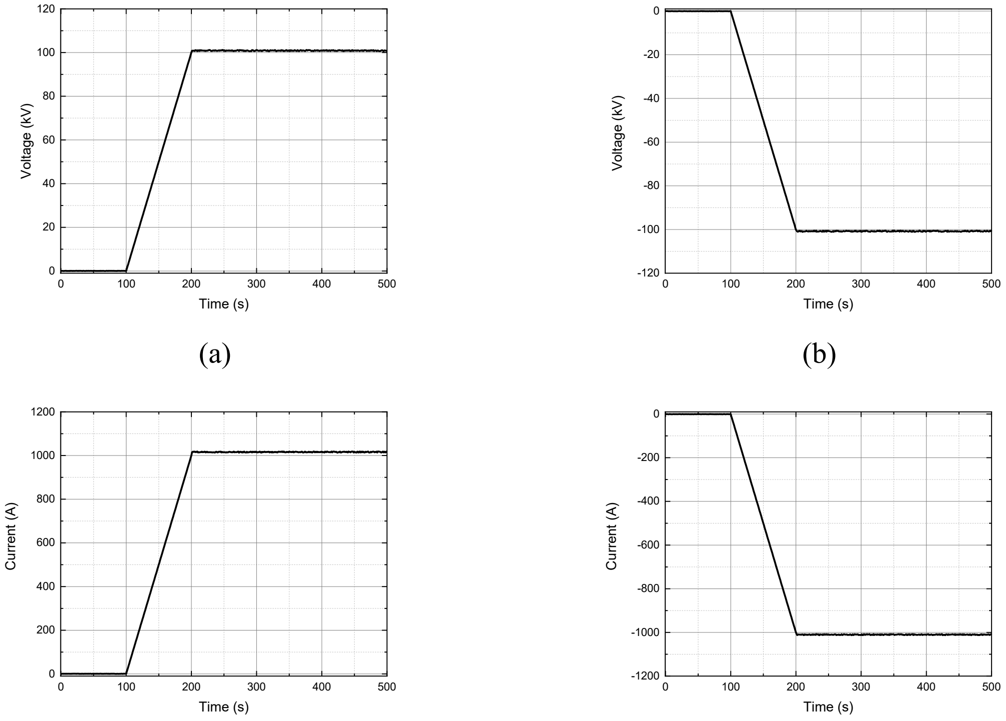
In the LNG flow test, Coriolis force mass flowmeter is used to measure LNG flow transported by a circulating pump. The result shows that LNG flow is measured to be 100 L/min, which satisfies the program requirement.

D. HIGH VOLTAGE INSULATION

In the high voltage insulation test, high voltage voltmeters are used to measure the voltages upon DC SEP prototype. The result shows that DC SEP prototype can keep operating at the voltage of ±148 kV for at least 1 hour without insulation breakdown. Its performance for resisting over high voltage has been proved.

E. FULL POWER OPERATION

In the full power operation test, the DC current supplier is used to apply currents to ±1000 A for the positive and negative superconducting cables, with the increasing rate of 10 A/s. DC SEP prototype keeps operating at the first state for 5 minutes. Then, the high voltage source in the negative circuit increases the voltage to -100 kV for the negative superconducting cable, with the increasing rate of 1 kV/s. DC SEP prototype keeps operating at the second state for 5 minutes. Consequently, the high voltage source in the positive circuit increases the voltage of positive superconducting cable to +100 kV, with the same increasing rate. DC SEP prototype keeps operating at the third state for 24 hours. At the end of the full power operating test, the currents and voltages of DC SEP reduce to zero with the current decreasing rate of 10 A/s and voltage decreasing rate of 1 kV/s respectively. The experimental waveforms of currents and voltages are shown in Fig. 10.



(a) (b)

(c) (d)

Fig. 10. The experiment results of the full power operating test. (a) voltage in positive circuit; (b) voltage in negative circuit; (c) current in positive circuit; (d) current in negative circuit.

The results show that the voltage at the positive pole of SEP is +100.6 kV; The voltage at the negative pole of SEP is -100.5 kV; the current at the positive pole of SEP is +1013 A; the current at the negative pole of SEP is -1007 A; the total electrical power of DC SEP prototype achieves 203.1 MW, as shown in Fig. 11.

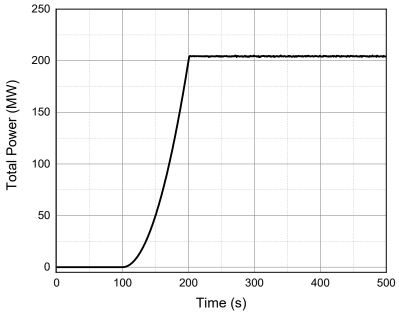


Fig. 11. The total transmission power of DC SEP.

VI. CONCLUSION

This study gives a structure design of ± 100 kV/1 kA DC SEP and theoretically analyzes its multiphysics coupled relationship between electric, magnetic, fluid and thermal fields. The multiphysics coupled model has been established and simulated by FEM. Simulation results indicate the distribution of multiphysics fields of DC SEP. High magnetic field region is located between the two superconducting cables and the cold fluids generally sink down when hot fluids float up. Moreover, a experimental platform has been designed and constructed, including a DC SEP prototype, a full power test platform and a cooling circulation system. Experiments for hybrid transmission of electricity and LNG have been conducted. The experiment results show that DC SEP prototype has a length of 31.2 m; its operating temperature zone is between 88.4 K and 93 K; the LNG flow is 100 L/min; the operating voltages of two superconducting cables in SEP are +100.6 kV/-100.5 kV; and their operating currents are +1013 A/-1007A; and the total electrical power is 203.1 MW.

The successful design and construction of the ±100 kV/1 kA DC SEP prototype has laid an significant theoretical and practical foundation for the development of technology for large-scale applications of hybrid energy transmission of superconducting electricity and fuel.

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