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Integrated Operational Characteristic Simulations of a ±100 kV/1 kA Superconducting DC Energy Pipeline Based on Multi-physics field Interaction

Jiahui Zhu, Pengzhen Huang, Ming Qiu, Panpan Chen, Hongjie Zhang, Yanfang Yang and Ercan Ertekin

***Abstract*—The DC superconducting energy pipeline (DC SEP) is a promising technology, which has the ability to transmit electricity and fossil energy such as liquefied natural gas (LNG) at the same pipeline so that LNG could serve as the refrigerant for the high-temperature superconducting (HTS) cables. The collaborative transportation of electricity and LNG increases the efficiency while lowering the cost. However, the operation performance of the SEP, which is crucial for HTS cables and LNG, is of greater complexity on account of multi-physics interactions. Herein, a ±100 kV/1 kA SEP model with electric, magnetic, fluid and thermal fields is established in COMSOL Multiphysics to analyze the temperature distribution of SEP via parametric scanning on SEP heat leakage and LNG flow rate. Finally, the relationship between temperature rise and LNG flow rate of a SEP has been estimated based on the interactions of the multi-physics fields. The results indicate that the temperature rises by 11.6 K for every kilometer of SEP. Moreover, the influences of heat leakage and LNG flow on temperature rise are revealed. Temperature rise increases proportionally with heat leakage and it decreases not monotonously with LNG flow rate. This study validates the feasibility of SEP and provides the theoretical references for the demonstration of SEP.**

***Index Terms*—DC superconducting energy pipeline (DC SEP); DC superconducting cable, liquified natural gas (LNG); multi-physics interaction simulation.**

I. Introduction

With the uneven distribution of energy and consumption between the east and west of China and the development of superconductivity and cryogenic technologies, DC superconducting energy pipeline (DC SEP) is a promising transmission system for the integrated transportation of electricity and liquid fuels in recent years. DC SEP consists of a DC high temperature superconducting (HTS) cable and a liquefied fuel transportation system. The DC high temperature superconducting cable has high current-carrying capacity and low losses, and the liquid fuel (such as liquid hydrogen, liquefied natural gas (LNG), ethylene, etc.) transportation system has high energy density and large transmission capacity. However, both DC HTS cable and liquid fuel require low temperature and adiabatic operating conditions, resulting in expensive transportation costs. If these two components could be combined using liquid fuel as coolant for superconducting cables, sharing the same refrigeration system and adiabatic layer, this expensive cost could be reduced and overall efficiency could be improved.

In 1995, Japan was the first to propose the idea of an integrated superconducting energy pipeline with superconducting cables cooled by liquid hydrogen [1]. In 2006, the University of Bologna, Italy, conceived a superconducting energy pipeline for transporting electrical energy and hydrogen over long distances of up to 10 km [2], and in 2010, Japan proposed a conceptual design for a long-distance superconducting energy pipeline with a distance of 100 km [3]. Russia successfully developed the world's first prototype of a superconducting energy pipeline consisting of a liquid hydrogen transport pipeline and a magnesium boride superconducting cable, and made a 30 m long prototype of a liquid hydrogen superconducting energy pipeline with a power transport capacity of 80 MW and a fuel transport capacity of 55 MW in 2013 [4], both of which were successfully tested.

Due to the fewer application, low safety and high cost of refrigeration of liquid hydrogen, and along with the continuous development of high-temperature superconducting materials and significant LNG resources, China began to turn to the research and development of LNG superconducting energy pipeline. The literature [5] and [6] both proposed a long-distance transmission system capable of transporting both electricity and LNG with higher capacity and efficiency. In [7], a general scheme of the system was proposed and a 100 kV/1 kA LNG superconducting energy pipeline was designed. The preliminary design of the bipolar DC superconducting cable, the dual-channel dewar tube and the whole energy pipeline were discussed in focus. The literature [8] designed and tested a 10 kV/1 kA LNG superconducting energy pipeline, in which the cable is insulated with LN2/CF4 mixture and the pipeline carries mixture of LNG/C3H8. The literature [9] put forward a conceptual design of 1 GW LH_2-LNG coaxial SEP and LNG is refrigerant.

But the integrated transportation of both electrical energy and LNG also brings more problems that are of necessity to be considered and solved. In a DC SEP, there are electric, magnetic, fluid and thermal coupled multi-physics fields at the same time. During the operation of the DC SEP, the magnitude of the current, the LNG flow rate and the temperature of

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Jiahui Zhu, Pengzhen Huang, Ming Qiu, Panpan Chen, Hongjie Zhang, Yanfang Yang are with the China Electric Power Research Institute, Beijing, 100192, China (e-mail: zhujiahui@epri.sgcc.com.cn)

Ercan Ertekin is with the University of Strathclyde, Glasgow, Scotland, G11 XQ, United Kingdom (e-mail: ercan.ertekin@strath.ac.uk)

the whole DC SEP need to be controlled within a certain range, otherwise it will lead to problems such as structural damage of the DC SEP. On the other hand, the experimental cost required for DC SEP is also very expensive. Therefore, it is important to conduct coupling multi-physics fields simulation of DC SEP, analyze the interactions of superconducting tapes current magnitude, LNG flow rate and temperature magnitude and distribution, as well as discuss the matching method of LNG flow rate for power and fuel hybrid transportation.

II. Multi-physics field coupling model

A. Structure of DC SEP

Fig. 1 shows the 3D geometric model of the DC SEP. The DC SEP has an adiabatic tube with a vacuum layer as the outer shell, and the three LNG pipeline and two bipolar DC superconducting cables are wrapped inside. The rest of the adiabatic tube is filled with liquid nitrogen, which is pressurized to heating at 85K, acts both as a cooling medium and an insulation medium. Table I shows geometric parameters of each component in the DC SEP. The geometric model cross-section of the DC superconducting cable is shown in Fig. 2.

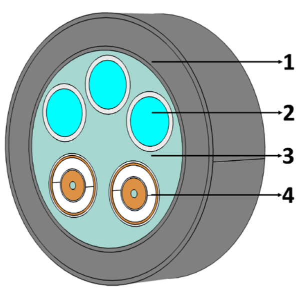

Fig. 1. The 3D structure of DC SEP. (1. the thermal insulating pipeline; 2. LNG pipeline; 3. LN_2; 4. DC superconducting cable).

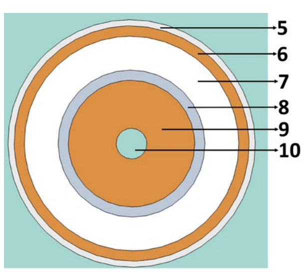

Fig. 2. The 2D cross-section of a DC superconducting cable. (5. the sheath; 6. shield layer; 7. the insulating layer; 8. the superconducting layer; 9. the copper former; 10. LN2).

The DC superconducting cable is consisted of liquid nitrogen tube, copper skeleton, superconducting layer, insulation layer, copper shield layer and protection layer from inside to outside. The liquid nitrogen tube provides liquid nitrogen return flow to cool the superconducting cable more effectively. The copper skeleton layer plays a supporting role and protects the superconducting layer by acting as a shunt in the event of a short circuit fault.

TABLE I
Geometric parameters of each component in the DC SEP

Component	Parameter	Value(mm)
Thermal insulation layer	Inner radius	122.5
	Outer radius	168.5
LNG pipeline	Inner radius	30.15
	Outer radius	36.5
DC superconducting cable	Inner radius	5
	Outer radius	40.25

B. Modeling method

In DC SEP, the superconducting cable generates an electromagnetic field, LNG and liquid nitrogen form a fluid field, and heat is exchanged between them, which forms a coupling multi-physical field in DC SEP.

For the second generation of HTS tape, the electric field strength $\boldsymbol{E}$ and current density $\boldsymbol{J}$ are established as the $\boldsymbol{E}$-$\boldsymbol{J}$ power law

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

where E_0=1×10^{-4}V/m is standard electric field constant, J_c is the critical current density of HTS tape, n is a constant determined by HTS material and n=21， J_{norm} is the modulus of $\boldsymbol{J}$.

The magnetic flux density $\boldsymbol{B}$ is established as a function of the current density J by Ampere's law

$$\nabla\times\boldsymbol{B}=\mu_0\cdot\boldsymbol{J} \tag{2}$$

According to Faraday's law, the functional relationship between the electric field strength $\boldsymbol{E}$ and the magnetic flux density $\boldsymbol{B}$ is given by

$$\nabla\times\boldsymbol{E}=-\frac{\partial\boldsymbol{B}}{\partial t} \tag{3}$$

Thus, the coupling of the electric field and current in the HTS cable with the full-space magnetic field has been achieved.

The Navier-Stokes equations are used in the model to describe the fluid motion, incorporating the conservation law of mass:

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

And the conservation law of momentum:

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

where $\boldsymbol{u}$ is the velocity vector of the fluid, ρ is the density of the fluid, p is the pressure of the fluid, $\boldsymbol{g}$ is the gravity acceleration of the earth, η is the dynamic viscosity of the fluid.

The forms of heat transfer in the DC SEP are heat conduction and heat convection. Heat conduction is mainly applied in HTS cable and heat leakage from outside, while the liquid nitrogen and LNG are dominated by thermal convection.

The equation describing heat conduction is Fourier's law, expressed as

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

where T is the temperature, k is the heat transfer coefficient of the material, ρ is the density of the material, C_p is the heat capacity at constant pressure of material, and q is the power loss per unit volume.

In DC SEP, h_f is the viscous loss generated by the fluid and the Joule heat generated by the HTS cable. The viscous loss is expressed as

$$h_f=\frac{64}{\mathrm{Re}}\frac{l}{d}\frac{v^2}{2\boldsymbol{g}}=\lambda\frac{l}{d}\frac{v^2}{2\boldsymbol{g}} \tag{7}$$

where Re is the Reynolds number of the fluid, λ is the resistance coefficient, v is the average flow rate of the cross section.

The Joule heat q_{SC} in the HTS cable is expressed as

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

When the DC SEP is in steady-state operation, the HTS tape is in superconducting state and almost no Joule heat is generated, so Joule heat can be neglected in this model.

III. Simulation Results and Analysis

The operating parameters of ±100 kV/1 kA DC SEP 3D FEM model are given in Table 2. Based on these settings, the multi-physics coupling characteristics of the DC SEP are simulated and analyzed.

TABLE II
OPERATING PARAMETERS OF THE DC SEP 3D FEM MODEL

Parameter	Value
Length	100 mm
Voltage of HTS cable	±100 kV
Current of HTS cable	1 kA
LNG flow rate	5-200 L/min
Heat leakage	0.5-1.5 W/m
Operating temperature	85-90 K

A. Electromagnetic field characteristics

When the current in HTS tape is 1 kA, the current density in HTS tape is uniformly distributed in the cross-section at steady state and the critical current has not yet been reached, as shown in Fig. 3.

Fig. 4 shows the magnitude and direction of the magnetic flux density $\boldsymbol{B}$ in the cross section of the DC SEP when the current in HTS tape is 1 kA. The magnetic flux density $\boldsymbol{B}$ mainly distributed in the HTS cable and outside the HTS tape, with a maximum value of 8.38×10^{-3} T. This indicates that the magnetic leakage in the superconducting DC energy pipeline is relatively small.

B. Fluid field characteristics

When the LNG flow rate is 100 L/min, the planned DC SEP test platform can drive the maximum LNG flow rate of 100 L/min approximately, the fluid velocity field streamline diagram is shown in Fig. 5(a). The liquid nitrogen cooled by the LNG sinks from the top to the bottom of DC SEP under the influence of gravity, and the converging flow forms two small vortices. Since both LNG and liquid nitrogen have a sinking part, the rest of the LNG and liquid nitrogen will also rise, thus filling the original position of the sinking fluid. From the fluid velocity field cloud diagram of Fig. 5(b), it can be seen that the maximum LNG flow velocity at the outlet is about 0.6 m/s and the maximum fluid velocity along the DC SEP occurs in the vortex caused by the sinking liquid nitrogen, which is about 1.0 m/s.

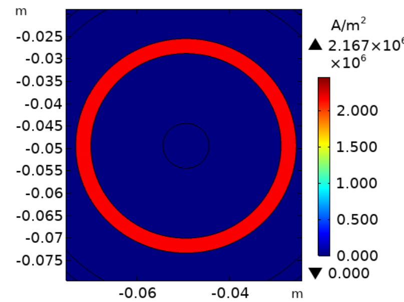


Fig. 3. Current density distribution in the cross-section of HTS cable.
(I=±1kA, steady state)

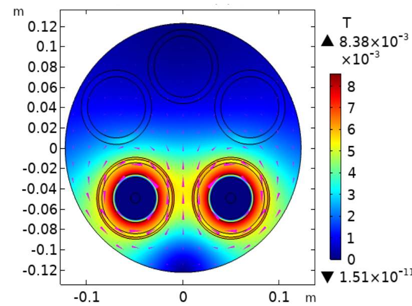
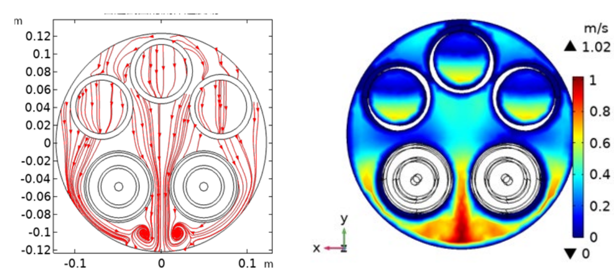


Fig. 4. Magnitude and direction of the magnetic flux density $\boldsymbol{B}$ in the cross section of the DC SEP.
(I=±1kA, steady state)



(a) (b)

Fig. 5. The fluid field diagram: (a)the fluid velocity field streamline; (b) the fluid velocity field cloud diagram.
(LNG flow rate=100L/min)

C. Thermal field characteristics

Fig. 6 shows the inlet and outlet temperatures of 100 mm DC SEP with heat leakage of 1 W/m and LNG flow rate of 100 L/min. At the inlet of the DC SEP, the temperature of LNG is 85 K; at the outlet, the temperature of top part of LNG is about 85.0016 K, the temperature of middle part LNG is about 85.0012 K, and the bottom LNG keeps 85 K. Therefore,

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under the influence of gravity, the HTS cable at the bottom of the DC SEP is cooled by the low-temperature liquid nitrogen, and the high-temperature liquid nitrogen, which is heated up by heat leakage, rises to the top of the DC SEP and is cooled by the LNG. Overall, in the thermal convection, liquid nitrogen works as a refrigerant to cool the HTS cable; the flowing LNG carries away the heat generated in the energy pipe by exchanging heat with liquid nitrogen.

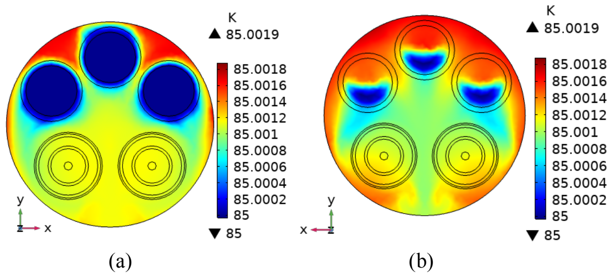

Fig. 6. The inlet and outlet temperature distribution of DC SEP: (a)the inlet; (b)the outlet.
(LNG flow rate=100L/min, heat leakage=1.0W/m)

D. The influences of heat leakage and LNG flow on LNG temperature rise

Fig. 7 shows the influences of heat leakage and LNG flow on LNG temperature rise. It indicates that LNG temperature rise increases linearly with the increase of heat leakage and decreases roughly with the increase of LNG flow rate.

Fig. 8 shows the variation of the maximum temperature rise of the LNG with the LNG flow rate at different heat leakages. When the heat leakage is 1.0 W/m, the LNG flow rates of 5, [50, 110], 200 L/min correspond to the high, the medium and the low LNG temperature rise, and they are 0.033 K/m, 0.015 K/m and 0.005 K/m. When the LNG flow rate range is [50,110] L/min, the increasing LNG flow rate fails to decrease the LNG maximum temperature rise. This is because the temperature rise is relatively small, resulting in less fluid heat convection. Moreover, viscous loss of LNG increases with the increase of LNG flow rate. Thus, the LNG flow rate ranges from 50 to 110 L/min is not sufficient for LNG to timely take away heat leakage and viscous loss for DC SEP. LNG flow rate should exceed this range for more optimal operation.

E. The influences of magnetic and thermal fields on critical current

We obtained the critical current of SEP to be 2576 A by FEM based on the maximum magnetic flux intensity inside the SEP for a series of given excitation currents and the critical current of superconducting materials under different magnetic flux density. Meanwhile, we establish a critical current test platform for SEP. A 1-meter-long DC HTS cable sample is wound and placed inside a cryogenic dewar, which is filled with liquid nitrogen, and the temperature of the liquid nitrogen reached to 85 K by pressurization. According to the criterion of 1 μV/cm, the critical current of the short sample at 85 K was measured to be 2600 A. Comparing the calculated value with the experimental measurement value, we can see that the relative error between the two is only 0.92% in Table 3.

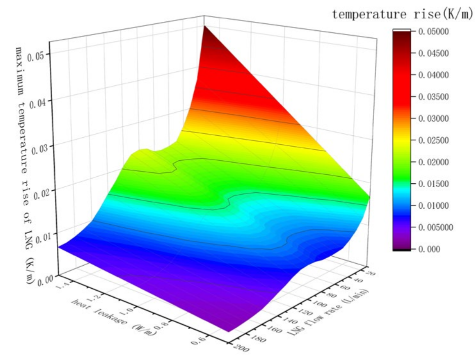

Fig. 7. The influences of heat leakage and LNG flow on LNG temperature rise.

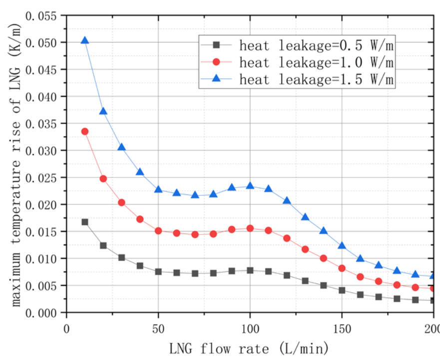

Fig. 8. The variation of the maximum temperature rise of LNG with the LNG flow rate at different heat leakage.

TABLE III
CRITICAL CURRENT COMPARISON OF CALCULATION AND MEASUREMENT VALUE FOR DC SEP

Critical current	Value
FEM calculation value	2576 A@85K
Experimental measurement value	2600 A@85K
Relative error ratio	0.92%

IV. CONCLUSION

DC SEP is an energy transmission system that achieves the integrated transmission of electricity and liquid fuel. In this paper, a finite element model of DC SEP with electric, magnetic, fluid and thermal coupling fields is established, and carried out computational analysis of electromagnetic field characteristics, fluid field characteristics, thermal field characteristics and critical current to reveal the operational performance of DC SEP cooled by LNG. And the relationship between heat leakage, LNG flow rate and temperature rise in DC SEP are analyzed. A critical current test platform for SEP is set up for a 1-meter-long DC HTS cable sample and the calculated critical current value agrees well with the experimental measurement one. These works validate that DC SEP is feasible for energy mixing transmission and provide the foundation for its future applications in power grid.

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