Design and Experimental Investigations on the Helium Circulating Cooling System Operating at Around 20 K for a 300-kvar Class HTS Dynamic Synchronous Condenser

Jun Tan, Renjun Xue, Han Tan, Tao Zhang, Yongjiang Zhao, Bangjian Zhao, Shiguang Wu, Yujia Zhai, and Haizheng Dang

***Abstract*—A project to develop a 10-Mvar high temperature-superconducting (HTS) dynamic synchronous condenser (DSC) is carried out by China Southern Power Grid Corporation. In order to cool the magnets to 20–30 K, a set of cryogenic system using circulating helium as the working fluid was developed, and it has been coupled and tested with the 300-kvar class dynamic synchronous condenser. Three cryogenic coolers are used as the cold source to provide more than 120 W@20 K cooling power. Cryogenic helium pump is employed to overcome a pressure drop of about 2.5 kPa induced by the helium gas circulating in the transfer tubes and heat exchangers. In the static tests coupled with the 300-kvar class dynamic synchronous condenser, the entire magnet was cooled to approximately 26.2 K by about 5 days. Once the rotor speeds up and reaches the design value of operation, the temperature rises slightly to about 26.6 K. Nowadays, the cooling system is upgrading and it will be served for the developed 10-Mvar DSC in the next year.**

***Index Terms*—Helium circulating, cooling system, 20 K, 10-Mvar HTS dynamic synchronous condenser.**

Manuscript received November 30, 2021; revised February 13, 2022; accepted February 28, 2022. Date of publication March 7, 2022; date of current version March 22, 2022. This work was supported in part by the National Natural Science Foundation of China under Grant 52076210, in part by the Shanghai Municipal Science and Technology Major Project under Grant 2019SHZDZX01, and in part by Shanghai Municipality under Grants 19ZR1465300, 20ZR1466100, 18511110100, 18511110101, 18511110102, 19511106800, 19511106801, 19511106802, and 2019-jmrh2-kj2. *(Corresponding authors: Jun Tan; Haizheng Dang.)*

Jun Tan is with the State Key Laboratory of Infrared Physics Shanghai Institute of Technical Physics, Chinese Academy of Sciences, Shanghai 200083, China (e-mail: juntan@mail.sitp.ac.cn).

Renjun Xue, Han Tan, Tao Zhang, Yongjiang Zhao, Bangjian Zhao, Shiguang Wu, and Yujia Zhai are with the State Key Laboratory of Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Sciences, Shanghai 200083, China, and also with the University of Chinese Academy of Sciences, Beijing 100049, China (e-mail: cryoxrj@163.com; hantancryo@163.com; cryotz@163.com; yjzhao13@163.com; zhaobjq@163.com; 1071264083@qq.com; cryozyj@163.com).

Haizheng Dang is with the State Key Laboratory of Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Sciences, Shanghai 200083, China, and with the University of Chinese Academy of Sciences, Beijing 100049, China, and with the Shanghai Research Center for Quantum Sciences, Shanghai 201315, China, and also with the Shanghai Boreas Cryogenics Company Ltd., Shanghai 201802, China (e-mail: haizheng.dang@mail.sitp.ac.cn).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TASC.2022.3156900.

Digital Object Identifier 10.1109/TASC.2022.3156900

I. Introduction

WITH the uniqueness in electromagnetics, superconducting materials have inherent advantages in power grid applications, such as superconducting cables, superconducting current limiters, superconducting motors and superconducting dynamic synchronous condenser (DSC), etc. With the applying superconducting materials to the excitation coil of the DSC, the loss of the excitation winding can be greatly reduced and the lifetime can be prolonged. The superconducting DSC also increases the air gap and reduces the synchronous reactance, thus enhances the voltage support capability. In addition, with the advantages of compact structure, small footprint and low cost of construction, the superconducting DSC has a strong appear to the power grid field and will play its unique role in the future [1]–[3].

For instance, American Superconducting Corporation (AMSC) developed a high temperature-superconducting (HTS) DSC and installed it on the Tennessee Valley Authority (TVA) grid. Two years later, TVA grid ordered five HTS dynamic synchronous condensers rated at 12 Mvar, and successful operation of the first prototype machine is expected to lead to release of these orders to production by TVA, which made HTS DSCs the first HTS commercial product for improving power grid reliability [4], [5].

Since the HTS DSC owns a high-speed rotating rotor, to provide direct continuous cooling to the rotary magnets is difficult. At present, helium gas circulating shows great advantages in such applications with its extremely low vibration and large remote distributed cooling capacity. And it has been investigated by several institutions for remote cooling of electro-technical equipment around 30 K, such as motors using superconducting materials of MgB_2 [6]–[9].

In 2018, A project to develop a 10-Mvar class HTS DSC is carried out by China Southern Power Grid Corporation. In order to solve some key technics, a 300-kvar class HTS DSC prototype was firstly designed and worked out [10], [11]. In this work, the detailed design of a helium circulating cooling system which aims to provide a cool capacity of 100 W@20 K to cool the HTS DSC will be introduced in detail, and the test results will be given as well.

1051-8223 © 2022 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission.
See https://www.ieee.org/publications/rights/index.html for more information.

Authorized licensed use limited to: Shanghai Institute of Technical Physics CAS. Downloaded on March 24,2022 at 01:52:00 UTC from IEEE Xplore. Restrictions apply.

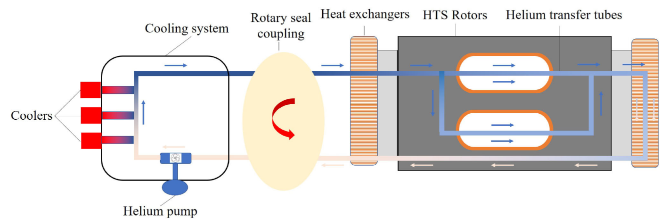

Fig. 1. A schematic of the HTS DSC system.

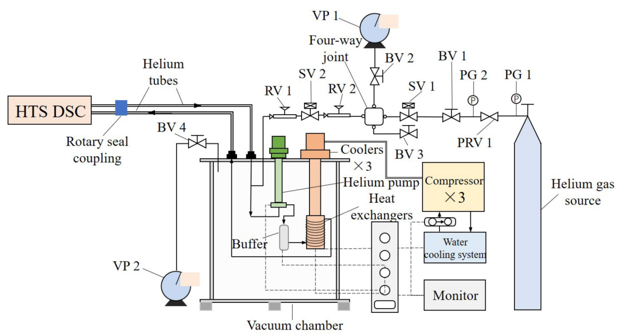

Fig. 2. The schematic of the cooling system. 1) VP represents vacuum pump, 2)BV represents ball valve, 3)PG represents pressure gauge, 4)PRV represents pressure regulate valve, 5)SV represents solenoid valve, 6)RV represents relief valve.

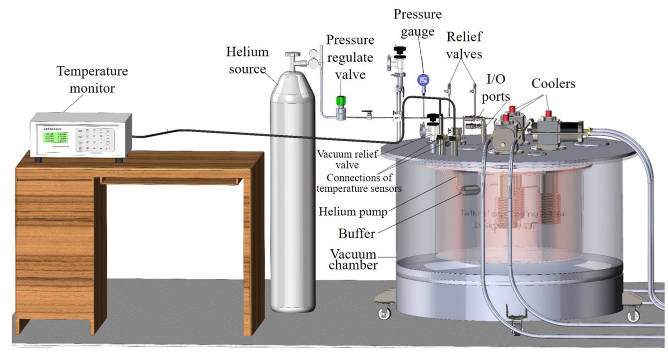

Fig. 3. The specific structure layout of the cryogenic system.

TABLE I
CALCULATION OF PRESSURE DROP

Component	Pressure drop (Pa)
Cold head exchangers	135
Helium transfer tubes	265.5
Connection tubes between heat exchanger and helium pump	51.7
Heat exchangers in HTS DSC	2000
Rotary seal coupling (estimated)	1000
Total pressure drop	3452.2
Pressure head of helium pump	4000

II. DESCRIPTION OF THE SYSTEM

A. The HTS DSC System

Fig. 1 shows a schematic of the HTS DSC system. The system consists of three main parts: the cooling system, the rotary seal coupling and the main body of the HTS DSC. The superconducting magnets in the distance can be cooled with the helium gas working as the medium. The helium gas is cooled in the specially designed heat exchangers which are attached at the cold head of the coolers, then, the cooled gas will be pumped to the rotary seal coupling by the cryogenic helium pump and finally reaches the HTS rotor. At present, a prototype of 300-kvar class HTS DSC system has been tested with the cooling system, and the cooling system is upgrading and it will be coupled with the developed 10-Mvar class DSC in the next year.

B. The Cooling System

Fig. 2 shows the schematic of the cooling system. The whole system includes four parts: the coolers, cryogenic helium pump, transfer tube line and the charge and relief tube line. Three coolers are employed to provide more than 100 W at 20 K and connected in parallel. The cryopump of Noordenwind type from Cryozone Inc is used as the circulator in the forced flow loop. The helium pump includes a high-speed motor with a long stainless-steel shaft to reduce the static conduction heat loss from the environment to the cryogenic zone. The pump housing is welded with 1/2” VCR type fittings for the easy connection with the transfer tubes. The Buffer is applied to stabilize the pressure after the helium pump and rectify the helium gas to get better heat exchange efficiency of the heat exchanger. The heat exchanger of the cold head employs a structure in which a spiral copper tube is wound on a copper cylinder. The tube and the cylinder are connected by brazing, and then the heat exchanger is tightly fixed with the cold head by screws. And the specific structure layout of the cryogenic system is shown in Fig. 3.

The transfer tube lines are two 5-meter stainless-steel tube wrapped with multi-layer insulation material to reduce radiation heat loss. Electropolish tube of 1/2” inch is used in order to reduce flow resistance.

The charge and relief tube line includes several different types of valves. The pressure regulate valve (PRV1) is connected with the helium gas source and it can be used to adjust the charge pressure. Four ball valves (BV1, BV2, BV3 and BV4) are employed to control the switching status of the line manually. BV1 is used to control the charge line, BV2 and BV4 are respectively used to control the connection to the vacuum pumps (VP1 and VP2), and BV3 is used for releasing the working gas manually for the case of helium circulating system purification. While the solenoid valves (SV1 and SV2) are employed to control the switching status automatically. The two relief valves are used to ensure the pressure of the whole circulating tubes in a safety state for the case of warm up.

Moreover, the flow resistance in the circulating tubes is also calculated and the results are shown in Table I. The working pressure is designed at 1 MPa and the temperature difference between the inlet and outlet of the load is set to 3 K. For the cooling system, there are three main parts of the flow resistance. First, that of the heat exchanger on cold head. Second, that of helium transfer tubes, which are two tubes of 5 meter connecting in series. Third, that of the 1-meter connection tube between the heat exchanger and helium pump, there are connected in parallel. Adding the flow resistance of the heat exchanger in HTS DSC and that of the rotary seal coupling, it can be found that the total flow resistance of the whole system is lower than the pressure

Authorized licensed use limited to: Shanghai Institute of Technical Physics CAS. Downloaded on March 24,2022 at 01:52:00 UTC from IEEE Xplore. Restrictions apply.

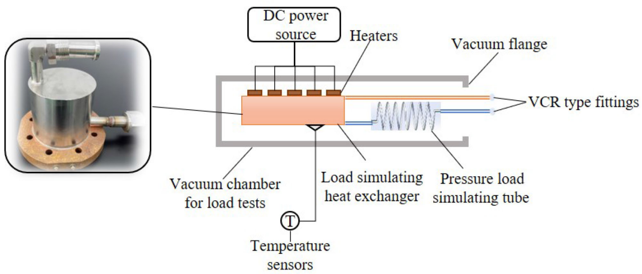

Fig. 4. The schematic of the simulated load tested with the cooling system.

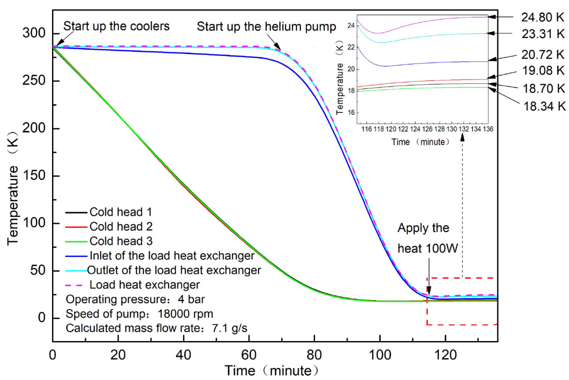

Fig. 5. The cooling down curve of the cooling system with the simulated load.

head of the helium pump, which can satisfy the demand of flow resistance.

III. Experimental Tests

A. Experimental Test With the Simulated Load

Before the cryogenic cooling system was coupled with the HTS DSC, the cooling capacity of the cryogenic system was evaluated through a simulated load, which is shown in Fig.4. A test cryostat has been designed, manufactured and connected to the helium loop line with a couple of VCR type fitting for test campaign. A specific designed heat exchanger is used to determine the effect on the helium loop cooling performance and estimate the cooling power which is expected to provide to the HTS DSC. A spiral tube is also employed to simulate the flow resistance in the heat exchanger in the HTS DSC. Five heaters are attached to the simulated load to provide a heat up max to 100 W. Through the heat balance method, the cooling capacity that the circulating helium gas can provide at the simulated load can be obtained.

In the cooling test with the simulated load, the pressure of the helium gas in the circulating pipes was maintained at 4 bar with the control of the charge and relief tube line, and the speed of the helium pump was set to operate at 18000 rpm. The cooling down curve of the system during the test is shown in Fig. 5.

In the beginning, start up the coolers, and the temperature of the cold head drops rapidly, reaching about 20 K after 80 minutes. Then, start up the helium pump, 36 minutes later, the temperature of the simulated load reached 20 K as well. When the temperatures stabilize, apply the heat of 100 W to the simulated load through the DC power source. It takes about

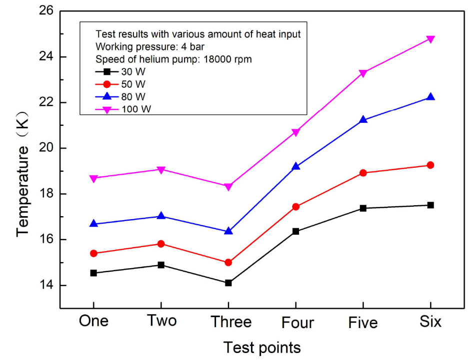

Fig. 6. Test results with various amounts of heat input on the simulated load. One presents cold head 1, Two presents cold head 2, Three presents cold head 3, Four presents the inlet of the load heat exchanger, Five presents outlet of the load heat exchanger, and Six presents the load heat exchanger.

20 minutes for the system to achieve a new thermal equilibrium. Finally, the temperature of the cooler was stabilized at about 19 K, the temperature of the simulated load was stabilized at 24.80 K, and that of the helium gas at the inlet and outlet of the simulated load was 20.72 K and 23.31 K, respectively.

Experiments have been conducted with different speeds of helium pump (including 10000, 12000, 15000, 18000, and 21000 rpm), the best cooling effect was achieved at 18000 rpm. According to the preliminary analyses, the following two reasons are found to explain it. First, the higher the speed of the helium pump, the greater the volume flow rate in the circulation pipeline, and the stronger the heat exchange between helium gas and cold head and that with the simulated load. The simulated load can be cooled to a lower temperature. At the same time, due to the increase of the flow rate, the flow resistance and pressure drop in the helium pipeline increase, and the kinetic energy loss increases. In addition, the power consumption of the helium pump also grows with its speed. The increase of these two items brings additional heat load to the whole system, which is eventually reflected as the temperature increase of the simulated load. Combining the above two factors, the helium pump speed is not as high as possible, there is an intermediate optimal value to obtain the best cooling effect.

Moreover, a series of tests on the cooling effect with different amounts of heat input applied on the simulated load is also conducted, including cases of 30 W, 50 W, 80 W, and 100 W. The specific results are illustrated in Fig. 6. With the heat on the simulated load increasing from 30 W to 100 W, the temperature of the simulated load increased from 17.51 K to 24.8 K accordingly, and the temperature difference between the simulated load and the circulating helium into the load also grows from 1.15 K to 4.08 K.

Through the experimental test of the simulated load, it can be found that, under this working condition, the helium circulating system can provide 100 W of cooling capacity to the simulated load and keep the temperature stable below 25 K, which has the ability to cool the HTS DSC to the required temperature. It also proved that the specially designed heat exchanger installed on the cold head can realize high-efficiency heat exchange among the cold head of the cooler, the heat exchanger and the circulating helium gas.

Authorized licensed use limited to: Shanghai Institute of Technical Physics CAS. Downloaded on March 24,2022 at 01:52:00 UTC from IEEE Xplore. Restrictions apply.

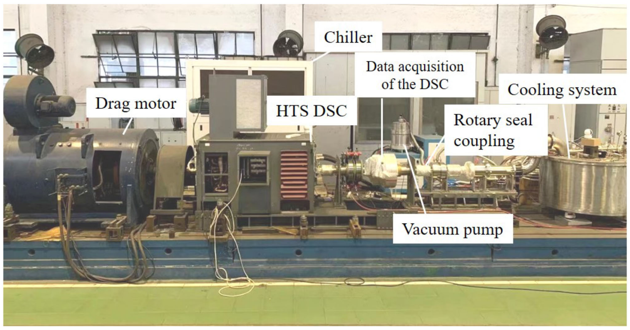

Fig. 7. Photograph of the test setup (the cooling system is coupled with the 300-kvar class HTS DSC prototype).

B. Experimental Test With the 300-kvar Class HTS DSC

After completing the test with the simulated load, the cooling system and a 300-kvar class HTS DSC prototype were coupled and tested. The coupled system is shown in Fig. 7. The entire system is composed of the drag motor, HTS DSC, data acquisition system, rotary seal coupling and the cryogenic system. The cryogenic helium pump and coolers are installed inside the vacuum chamber, helium gas transfer tubes are connected to the rotary seal coupling through the VCR type fittings inside of the vacuum pumping tubes.

The vacuum chamber of the HTS DSC and that of the cooling system are connected in parallel to a set of vacuum pump to provide a vacuum environment below 10^{-4} Pa during the whole test. Two sets of data acquisition device are used, one is used to monitor the temperature, current and voltage in the HTS DSC, and the other is used to monitor the temperature of key parts of the cooling system, the speed of the helium pump, and the vacuum degree of the vacuum chambers.

During the cooling test coupled with the HTS DSC prototype, the pressure of the circulating helium gas is maintained at 400 kPa. The detailed cooling down curves of the whole system are shown in Fig. 8(a). At the beginning, only the cryogenic coolers were activated. After about 2 hours, the temperature of the cooler reached 20 K. At this time, the helium pump was turned on and its speed was adjusted to 18000 rpm gradually. After about 120 hours, the temperature of the entire system reached a steady state. Finally, the temperature of the HTS magnet is 26.2 K, that at the inlet of the heat exchangers of the HTS magnet reaches 21.4 K. While for the cooling system, the temperatures of the three coolers are 18.5 K, 19.6 K and 19.6 K, respectively. And that at the inlet and outlet of the helium pump are respectively 35 K and 43.1 K. The test results indicate that the designed cooling system can provide an excellent remote cooling which can satisfy the cooling temperature demand of the HTS DSC.

According to the test results, it can be found that there exists a temperature difference of 1.1 K among the cold head of the three coolers. By the preliminary analyses, the following reason is found to explain this difference. The helium transfer tube pipeline is divided into three parallel pipelines at the outlet of the helium pump, each of which is connected to the heat exchanger of the cold head. The distance from the outlet of the helium pump to each cold head is different, which leads to differences of length and elbow in the connecting tubes. Therefore, the flow rate entering each branch differs, which will affect the heat exchange between the specially designed heat exchanger and the circulating helium, and is finally reflected in a temperature difference between the coolers. It should be noted that the thermometers for measuring the temperature of the inlet and outlet of the helium pump are installed on the stainless-steel connecting tubes on both sides of the pumping house. As the thermal conductivity of stainless steel in such low temperature zone is relatively low, the measured temperature will be higher than that of the helium gas at these two positions.

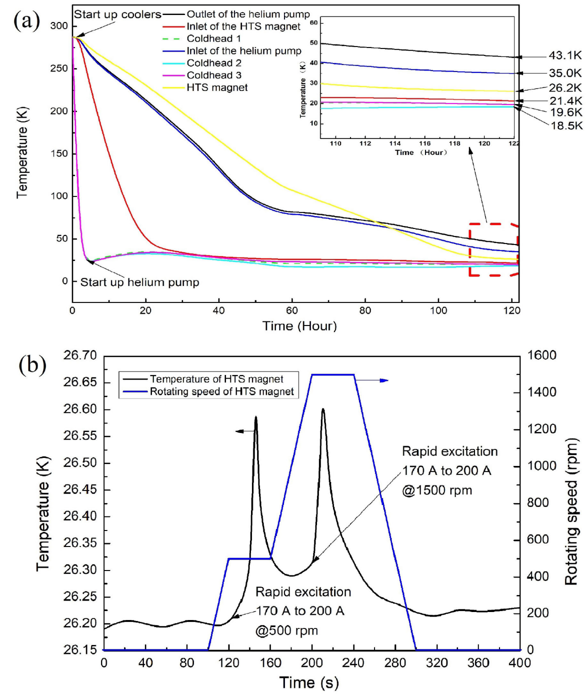

Fig. 8. (a) Cooling down curves of the system coupled with the 300-kvar class HTS DSC prototype. (b) Rapid excitation test from 170 A to 200 A.

Then, the tests of rotating excitation were conducted and test results are shown in Fig. 8(b). The two rapid excitations were carried out at 500 rpm and 1500 rpm, with the excitation current increasing from 170 A to 200 A in 1 s, the temperature of rotor magnet rises only about 0.5 K, which shows well temperature steady of the cooling system.

IV. Conclusion

A cooling system that can provide a remote cooling capacity of 100 W@20 K by circulating helium gas for the HTS DSC system is designed, fabricated, and tested. Experimental results show that, coupling with a prototype of the 300-kvar class HTS DSC system, the HTS rotary magnet was successfully cooled to 26.2 K and showed excellent performance, which verifies that the designed helium circulating cooling system is very suitable for the applications of HTS rotary magnet and can meet the cooling demands of the 300-kvar HTS DSC. Nowadays, the cooling system is upgrading which aims to provide a cooling power of 200 W@20 K for a 10-Mvar class HTS DSC system, and relevant tests will be put forward in the next year.

Authorized licensed use limited to: Shanghai Institute of Technical Physics CAS. Downloaded on March 24,2022 at 01:52:00 UTC from IEEE Xplore. Restrictions apply.

REFERENCES

[1] F. O. Igbinovia, G. Fandi, Z. Muller, and J. Tlusty, “Reputation of the synchronous condenser technology in modern power grid,” in *Proc. Int. Conf. Power System Technol. (POWERCON)*, 2018, pp. 2108–2115.

[2] S. S. Kalsi, D. Madura, and M. Ingram, “Superconductor synchronous condenser for reactive power support in an electric grid,” *IEEE Trans. Appl. Supercond.*, vol. 15, no. 2, pp. 2146–2149, Jun. 2005.

[3] E. Kosuge *et al.*, “Development of helium transfer coupling of 1 MW-class HTS motor for podded ship propulsion system,” *J. Phys. Conf. Ser.*, vol. 234, no. 3, Jun. 2010, Art. no. 032032.

[4] S. Kalsi, D. Madura, T. MacDonald, M. Ingram, and I. Grant, “Operating experience of superconductor dynamic synchronous condenser,” in *Proc. IEEE/PES Transmiss. Distrib. Conf. Exhib.*, 2006, pp. 899–902.

[5] S. Kalsi, D. Madura, and M. Ross, “Performance of superconductor dynamic synchronous condenser on an electric grid,” in *Proc. IEEE/PES Transmiss. Distrib. Conf. Expos.*, 2005, pp. 1–5.

[6] T. Trollier, J. Tanchon, Y. Icar, and A. Ravex, “Remote helium cooling loop for laboratory applications,” *Cryocoolers*, vol. 17, pp. 503–510, 2012.

[7] T. Trollier, A. Ravex, J. Tanchon, and J. Lacapere, “20 K cryogenic helium forced flow circulation loop,” *Cryocoolers*, vol. 19, 2016, pp. 547–556.

[8] E. Kosuge *et al.*, “Development of helium transfer coupling of 1 MW-class HTS motor for podded ship propulsion system,” *J. Phys. Conf. Ser.*, vol. 234, no. 3, Jun. 2010, Art. no. 032032.

[9] J. Urbahn, R. Ackermann, X. Huang, E. Laskaris, K. Sivasubramaniam, and A. Steinbach, “The thermal performance of a 1.5 MVA HTS generator,” in *Proc. AIP Conf.*, 2004, vol. 710, no. 1, pp. 849–858.

[10] P. Song *et al.*, “General design of a 300-Kvar HTS synchronous condenser prototype,” *IEEE Trans. Appl. Supercond*, vol. 30, no. 4, Jun. 2020, Art. no. 5206905.

[11] Q. Wu *et al.*, “Development and testing of a 300-kva HTS synchronous condenser prototype,” *IEEE Trans. Appl. Supercond*, vol. 31, no. 5, Aug. 2021, Art. no. 5201805.

Authorized licensed use limited to: Shanghai Institute of Technical Physics CAS. Downloaded on March 24,2022 at 01:52:00 UTC from IEEE Xplore. Restrictions apply.