A Cooling Station for a 10 kV HTS Power Substation

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ABSTRACT:A 10 kV High Temperature Superconducting power substation with a cooling system was developed and has been put into operation in power distribution system for more than three years. The working conditions, heat resource and the distribution character of the four apparatuses working at the 10 kV/630 kVA HTS substation were analyzed. The heat load is distributed along the length for the cable for which thus a forced enclosed circulation system is necessary; while it is concentrated within only several cryostats for the other three HTS apparatus for which it is enough to cool only with an opened loop cooling system by consuming of liquid nitrogen. And an independent cooling system with refrigerator for the 1 MJ SMES is a good selection due to the different working temperature range. Based on the analysis and discussion, a concentrated evaporative cooling station which includes an opened loop cooling system without circulation and a forced circulation system with a closed circle was designed and constructed.

INTRODUCTION

With the rapid growth of power grid capacity, there is growing need for a reliable and sustainable electric power infrastructure. Superconducting power technology is believed to have the potential of improving the efficiency and robustness of the power grid in future. [1-2].

Due to its many advantages compared with that of conventional methods, superconducting power technology was considered to be a competitive candidate for the future power grid: the superconducting cable would achieve large capacity transmission; the superconducting transformer could increase the efficiency while decrease the bulk of transformer; the superconducting fault current limiter (SFCL) provides a new option for the grid to enhance the security and stability; the superconducting magnetic energy storage system (SMES) may play an important role to improve the quality of electrical energy in the future grid for the renewable energy grid[3-7]

Over the past decade, both the manufacturing technology and properties of high temperature superconducting (HTS) tape have been made great progress. It can be produced with industrialized technology and several companies have had the commercialized supply ability of HTS tape., and we can easy to obtain the 1G and 2G HTS tape (the first and second generation HTS tape made of different basement material of Bi and Y, respectively) from market.

Based on the great progress of the manufacturing technology and properties of HTS tape, studying on the fabrication and application technology of superconducting apparatus have been promoted greatly in past decade, several demonstration projects studies have been completed successfully, many new projects and practical application are still being promoted around the world. This projects includes a 5/10 MVA HTS transformer, a 138 kV/600 m HTS cable and a 138 kV/900A SFCL in USA; a 500 m/22.9 kV HTS cable in Korea; a 15 MVA class SFCL in Italy; a 66 kV/1.75 kA HTS cable and a 2 GJ Class YBCO SMES in Japan, and so on [8-13].

IEECAS (Institute of Electrical and Engineering, Chinese academy of Sciences) has been promoting the R&D of superconducting technology in the past fifteen years. And a 75 m /10.5 kV/1.5 kA three-phase AC HTS cable (75 m HTS cable), a three phase 630 kVA/10.5 kV/400 V HTS transformer (10 kV HTS transformer), a three phase 10.5 kV/1.5 kA SFCL (10 kV SFCL), and a 1

MJ/0.5 MVA SMES (1 MJ SMES) were successfully developed and demonstrated in past decade [14-17]. And then a 10 kV HTS substation, into which these four HTS power equipments were integrated, were developed and put into operation in the power distribution system since 2011. After running for 3 years, in 2014, a 10 kV/ 1250 kVA superconducting transformer, which was used to replace the 630 kVA/10.5 kV/400 V HTS transformer，was developed and demonstrated in the substation. The capacity of the 10 kV HTS substation was improved to 1250 kVA. And there is no upgrade for the cooling system after the capacity of the 10 kV HTS substation was increased to 1250 kVA. Figure 1 shows the 10 kV HTS substation and its four apparatuses and the cooling system. Figure 2. gives the structure of the 1250kVA HTS transformer.

Figure 1.the 10 kV HTS power substation

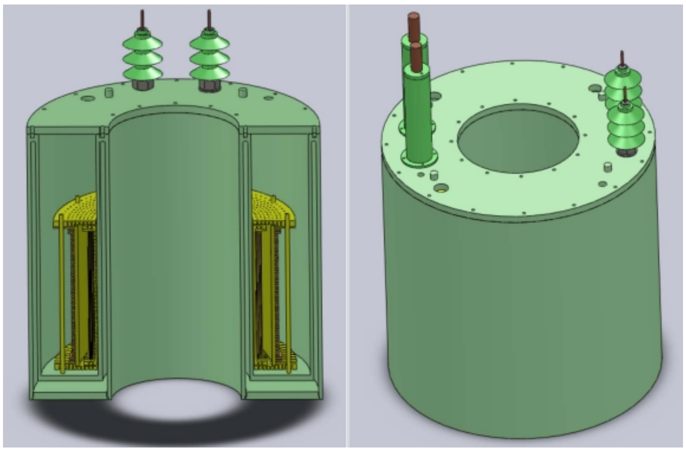

Figure 2. The sketch structure of the 1250kVA HTS transformer

The working conditions, the heat resource and the distribution character of the four apparatuses working at the 10 kV/630 kVA HTS substation were analyzed. Based on the analysis for the heat resource and distribution character, a concentrated evaporative cooling station which includes an opened loop cooling system without circulation and a forced circulation system with a closed circle was designed and constructed. The structure of the cooling station was discussed.

WORKING CONDITION OF THE HTS APPARATUSES

As showed in the sketch of Figure 2 below, the 10 kV HTS substation connects with the 110 kV power transmission line by a step-down transformer and the loads of user by step-up transformer. The FCL and the HTS power cable were connected in series with the HTS power transformer in the higher voltage side and the lower voltage side; and the SMES was connected shunt with a 10.5 kV bus. Figure 3 gives the Topology structure of the superconducting power substation.

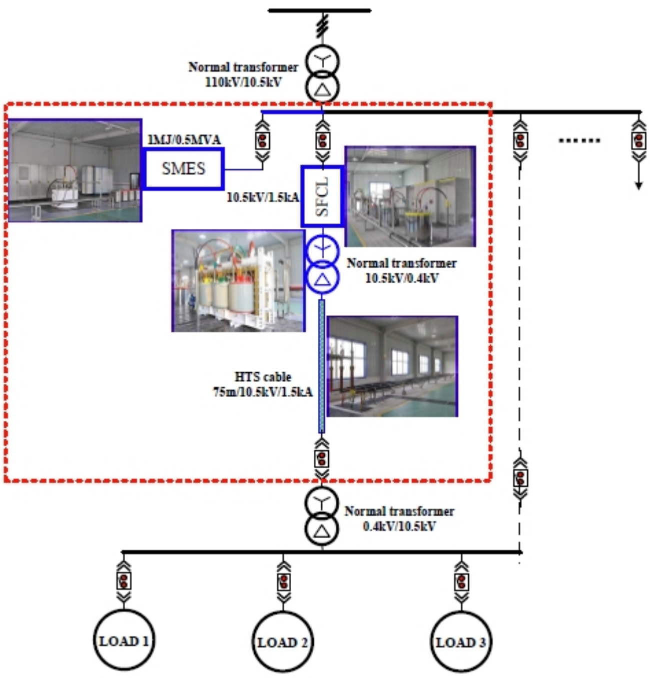

Figure 3.Topology structure of the superconducting power substation

The rated voltage of the HTS transformer is 10.5kV/0.4 kV and rated current 909 A with capacity of 630 kVA. Its windings were developed with HTS pancake coils. The superconducting windings were set within three cryogenic dewars made of nonmetal material with separated structure. The HTS transformer works at 77 K~80 K with refrigeration of normal latent heat of vaporization of the liquid nitrogen by consumption of it.

The HTS power cable, of which the insulation structure is warm-dielectric type, was developed in 2004. The rated designed current of the HTS cable is 1500 A, and the max current carried in the 10 kV HTS substation is only less than 1000 A. So the heat load working in the station is much lower than that of the cable working under rate current. The HTS cable was cooled by the normal circled liquid nitrogen without refrigeration by reducing pressure of liquid nitrogen or refrigerators, and the normal latent heat of vaporization of the liquid nitrogen is enough to keep the superconducting conductor to work at 77 K -80 K.

The SFCL was developed in 2005. And a bridge-type structure, in which the HTS coil and the resistors were used as two bridge arms, was designed, and the fault current would be limited by both the HTS coils and the resistors. The SFCL and the prospective fault current of 3.5 kA was reduced to 635 A. The HTS coils were put into three cryogenic containers made of nonmagnetic stainless steel. The HTS coils work under liquid nitrogen condition with temperate of 77 K -80 K.

The coil of SMES was fabricated by BSSCO tape and operated under 4.2 K. The max stored energy of the HTS coil is 1 MJ, and the rated voltage 10.5 kV with the output power 500 kVA under 50 Hz condition. The coil was also set within a cryogenic containers made of nonmagnetic stainless steel. The cryogenic container, which was designed with an inner tank and a shielding layer, was filled with liquid helium in the inner tank and liquid nitrogen in the shielding layer.

HEAT RESOURCE OF THE HTS APPARATUSES

There are four losses existing in a HTS apparatus including Joule heat loss, Conductive heat, AC loss and Leaked-in heat.

Joule heat loss is contributed mainly by resistance of the current lead including the transitive flexible conduct and their joints. It is determined by the current a HTS apparatus carries and the conductive property of the material of a current lead. The current lead is usually a main source of heat loss due to the existing both or Joule heat and conductive heat. To minimize the heat loss resulted by the current lead, the length and the cross section should be optimized according the thermal conductivity of the conductor $\lambda(T)$, electrical resistivity ρ by the (1) below.

$$\frac{LI}{S}=\sqrt{\frac{2}{\rho}\int_{T_L}^{T_H}\lambda(T)dT} \quad (1)$$

Where L is the length of the current lead; I is the rated current of the current lead; T_H and T_L are the working temperature at the two ends of the current lead; ρ , λ and S are electrical resistivity, thermal conductivity and cross section of the current lead respectively[18].
AC loss occurred due to the alternating magnetic field is when the HTS apparatus carries ac current. And the AC loss still exists under DC working condition due to the existing of harmonic components of the current. AC losses consist of hysteresis loss, eddy current loss and coupling loss. According to the two references, the hysteresis loss can be analyzed by two complex analysis formulas when the HTS tape works under perpendicular and parallel magnet field condition respectively. The hysteresis loss is proportional to the frequency f and the full penetration field B_P which is determined by μ_0、J_c and d , here J_c is the critical current density, μ_0 the magnetic permeability of vacuum and d the half-thickness of the HTS tape. The 1st generation HTS tape of BSCCO is a kind of multi-filament composite conductor and there are many filaments within it. The alternative magnetic field induced by AC will cause coupled field within the filaments, and this will induce an alternative electric field and then a coupled current occurs around a loop across the normal conducting of the filaments. The eddy current and the eddy loss exist in the matrix of the normal conductor of reinforcing layers, such as the stainless steel or the brass, due to the magnetic field. It would be significant under the perpendicular magnetic field. The whole AC loss occupies a certain proportion of heat loss when the HTS apparatus carries AC current, it should be minimized by optimization design to decrease the vertical component of magnet field imposed on the HTS tape, controlling the frequency of working current, and so on [18-19].
The leak-in heat from cryostat, which is determined by the performance of a cryostat, affected by its structure and material, is also an important section. The cryostat structure of a HTS apparatus is usually designed to be thermal insulated with high vacuum and multilayer insulation generally. The radiation heat loss induced by the nature property of material, the conductive heat loss caused by the inner wall of cryostat, and the convective heat determined by the vacuum degree, exists in cryostat at the same time. The performance of cryostat material has great influence on its thermal property because it determines the ability of maintaining vacuum. The cryostat made of nonmetallic material has poorer thermal insulation property generally than that made of metal. The cryostat of the HTS transformer is made of nonmetal material; and the cryostat of the other three apparatus is made of metal material.
The max heat loss of the HTS cable is less than 900 W under AC 1500 A working condition. The cable carries only 900 A max in the substation, its total heat loss is also much less than 900 W. The total heat loss of the HTS transformer is less than 381 W under rated working station. The AC loss, the joule heat coming from the current and the heat loss leaked-in from cryostat contributed about 30~40% respectively. The total heat loss of the SFCL is about 100 W/phase and 300 W for the total SFCL unit.
The HTS coils of the 1 MJ SMES works at 4.2 K with rated working current of DC 565 A. It can be estimated that the heat loss of the 1MJ SMES is less than 5 W at 4.2 K, which was agreed with the output power of its refrigerator.

THE COOLING SYSTEM OF THE SUBSTATION

The three HTS apparatus including the HTS cable, the transformer, the SFCL work around 77 K. The total heat loss of the three HTS apparatus analyzed above is much less 1581 W due to the heat loss decrease of the HTS cable which carries only 60% of its rated current.
Even the HTS coils of the 1 MJ SMES works at 4.2 K with less than 5 W at 4.2 K, the liquid nitrogen is also necessary because of the consumption of the shielding layer of the cryostat for the liquid nitrogen. So the liquid nitrogen is necessary for the four HTS apparatus of the 10 kV substation. The heat loss existed in the HTS transformer, the shilding layer of the SMES and the SFCL concentrates within several cryostats. It is enough to cool, only by consuming of liquid nitrogen for the three HTS devices, without the enclosed circulation for liquid nitrogen. So an opened loop cooling system without circulation was able to meet the demand for cooling the three HTS apparatus.
The heat load of the HTS cable is distributed along the length of the three cryostat envelope pipes of phase A, phase B and phase C. The heat generated in the cable due to the AC loss or the heat leaked-in from the cryogenic envelopes has to be taken away in time. And a forced circulation system with closed circle for liquid nitrogen was necessary to cool the HTS cable.
Different from the other three HTS apparatus, the 1MJ SMES works at 4.2 K with heat loss of less than 5 W; and an independent cooling system has to be designed for it.
According to the heat load and the distribution characters, a concentrated evaporative cooling station was designed and constructed. Figure 4 gives the Topology structure of the concentrated evaporative cooling station.

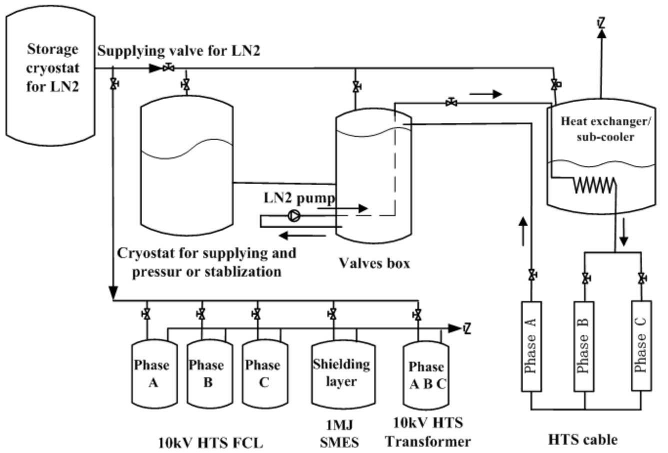

Figure4. the Topology structure of cooling station

It can be found that there are an opened loop cooling system without circulation and a forced circulation system with a closed circle in the concentrated evaporative cooling station. The concentrated evaporative cooling station includes a storage cryostat of liquid nitrogen, a cryostat used for supplying and stabilization, a valves box, a pump for liquid nitrogen, a cryostat used for heat exchanger, and several cryogenic pipes and valves used to connect the cryostat with the HTS apparatus. The opened loop cooling system was used to cool the SFCL, the shielding layer of the SMES, and the transformer. The liquid nitrogen was injected into the three HTS apparatus by the self pressure of the storage cryostat.
In the opened loop cooling system, an automatic nitrogen controlling system, in which a signal process system and a LED level meter were used, for liquid nitrogen of HTS transformer was developed as reported in [20] of our research before. In the system, several pneumatic solenoid valves were used to control the supplement of liquid nitrogen. The solenoid valves were controlled by the liquid nitrogen level which was taken by a level gauge. Figure 5 gives the sketch of the automatic controlling system for nitrogen supplement.

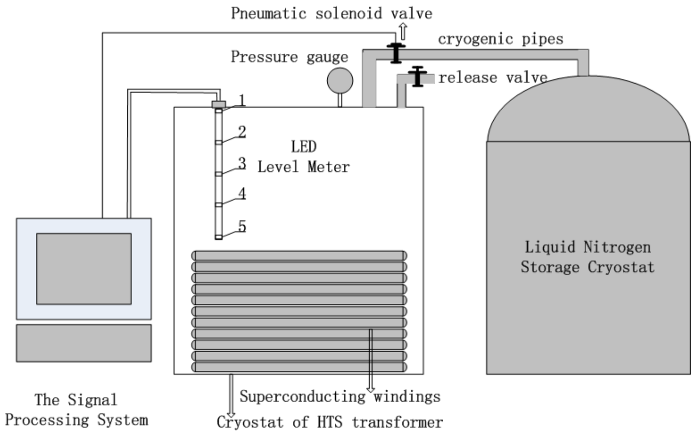

Figure 5. Automatic nitrogen replenishing device

In the forced circulation system which was used to cool the HTS cable, a liquid nitrogen pump, a valves box and an exchanger were designed. Liquid nitrogen was pumped from the heat exchanger into the phase B and phase C of the HTS cable, and then flushed out from the phase A. A cryogenic valves box and cryogenic heat exchanger was designed to control the distribution of liquid nitrogen and exchange for heat respectively.

So the cooling station supports the cooling resource for three HTS apparatus and the shielding layer of SMES. The difference exists in an opened loop or a closed loop cooling system was selected for the circulation of liquid nitrogen.

The cooling system for the 1 MJ SMES is independent from that of the other three HTS apparatus; and 4 GM refrigerator, of which the output power is 1.5 W per one at 4.2 K, were employed to cool the SMES, and the total output of refrigerating capacity is about 6W. The total output is larger than the heat loss of the SMES. So the output power of the three is almost able to meet the demand to maintain its running. The 4th GM refrigerator is run intermittently and controlled by the pressure of the helium in the SMES. Figure 6 below is a picture of the cooling station and the 4 refrigerator for the SMES.

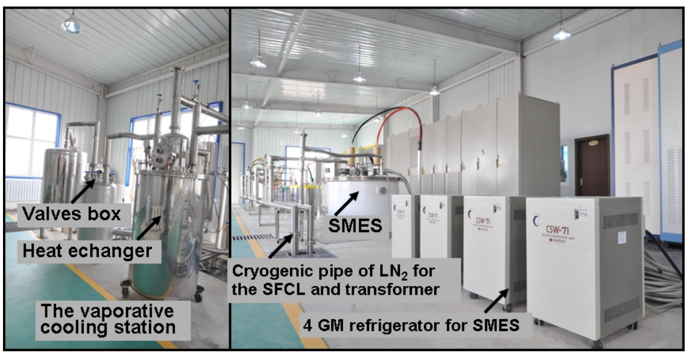

Figure 6. Cooling station and the 4 refrigerator for the SMES

The mean consumption tested for liquid nitrogen in fact during the normal operation is about 1100 L/day corresponding heat loss of 2000 W. The superconducting power substation was put into operation since 2011, and was stopped in 2014. The HTS apparatus and cooling system works well during the term.

CONCLUSION

A 10kV HTS power substation，into which four HTS apparatus were integrated, was developed and has been put into operation for more than three years.
The working conditions, the heat resource and the distribution character of the four apparatuses working at the 10 kV/630 kVA HTS substation were analyzed.
The AC loss can be neglected for the HTS cable and the SFCL during the design of the refrigeration system. The heat loss comes mainly from the leaked-in heat and the current lead due to the Jour heat and conductive heat. The heat load is distributed along the length for the cable, while concentrates within several cryostats for the other three HTS apparatus. It is enough to cool only by consuming of liquid nitrogen for the three HTS devices without the enclosed circulation for liquid nitrogen. Based on the analysis above, a concentrated cooling station which includes an opened loop cooling system without circulation and a forced circulation system with a closed circle was designed and constructed. The structure of the cooling station was discussed. Conclusion

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