A prototype 4m, 2kA, AC HTS power cable system

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A project to develop a 30m, 35kV/2kV, 3 phase, warm dielectric HTS power cable system has been installed in a power grid at Puji substation of Kunming, Yunan province at April of 2004. To enhance the understanding of the basics of a HTS cable system and to prepare the fabrication techniques and skills, a 4m system with terminations and cryogenics was built and tested. In this paper, we will present the detailed parameters of the cable system, update the progress of the work. Some experimental results, and analytical discussions are included.

INTRODUCTION

As compared to conventional power cables, High Temperature Superconductor (HTS) cables have larger capacity, about 3-5 times to a conventional cable at a same cross section, and smaller transmission line loss, about 50% of that of a conventional cable[1]. Therefore, HTS cables are especially attractive for metropolitan areas, where increasing load dictates that the existing conventional cables have to be replaced. Till now, 2 sets of HTS cable system have been successful installed in a power grid in the world [1]. In the spring of 2004, a 3 phase 30m warm dielectric (WD) HTS cable with 35kV/2kArms capacity has also been installed at Puji substation of Kunming, Yunan Province of China.

To enhance the understanding of the basics of a HTS cable system and to prepare the fabrication techniques and skills, a 4m system with terminations and cooling system was built and tested. In this paper, the detailed parameters and structure of the prototype system are introduced, and some test results are also given.

DESCRIPTION OF THE 4m HTS POWER CABLE SYSTEM

A 4m HTS cable system, which include the cooling system, terminations, and cable was built in April of 2003, the detailed parameters are listed in Table 1 and the flow diagram of the cooling system and the schematic diagram of the HTS cable and terminations are shown in Figure 1 and Figure 2 respectively.

The cooling system is a closed cycle system as shown in Figure 1. The coolant LN_2 is pumped into the sub-cooling tank, then into the HTS cable and brings heat out, and discharging to the LN_2 pump tank. The LN_2 pump is a partial emission centrifugal type with a hermetically sealed motor. The motor is controlled by a variable frequency drive (VFD). This allows adjustment of the pump speed to produce any desired head and flow within the available power range. The pump is so designed that the pump housing and impeller are in LN_2 and the motor is at atmospheric conditions. The pump and motor are separated by a 31-inch, thin-walled shaft and housing, which minimize heat input from the motor into the LN_2 [2]. The capacity of the GM refrigerator is 250W@70K-50Hz (300W@70K-60Hz). As shown in Figure 1, Refrigerator cools LN_2 in sub-cooling tank, then the sub-cooled LN_2 cools the cycling LN_2 of the system. The sub-cooling tank is at negative gauge pressure during operating, so a vacuum pump can be prepared to compensate unexpected cooling power. This is very economical and reliable.

Table 1 Parameters of prototype 4m HTS cable system

Components	Item	Parameter
Conductor of cable	Material	Bi-2223
	Dimension	4.2×0.22mm
	Ic (77K,0T)	>55A
	Bending Strain	0.5%
	Minimum bending radii	25mm
	Tension stress	100Mpa
Cable	Former	SUS304,18/26.0mm,flexible
	Numbers of conductor layers	6
	Winding angle of conductor (inside to outside)	35º/30º/19º/-20º/-34º/-44º
	Dielectric between conductor layers	Kaputon,25×0.1mm
	Spacer	Teflon,2/4mm
	Cryostat	SUS304,40/76.6mm,flexible
	Cooling structure	Counter-flow cooling
	Rated current	2000A
Termination	Current lead	Cu
	Epoxy pipe	Epoxy+ Silica aerogel
	Contact resistance	<0.4μΩ
	Cryostat	SUS304, rigid
Cooling system	Cooling mode	Closed LN_2 Cycle
	Cooling capacity	250W@70K (only refrigerator) 750W@70K(with the aid of a vacuum pump)
	Refrigerator	GM (AL300)
	LN_2 pump	Bncp-30c-000

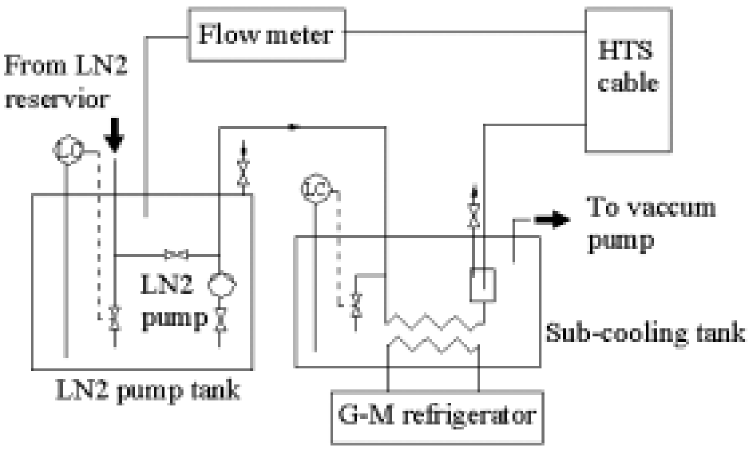


Figure 1 Flow diagram of cooling system

The 4m HTS cable system is composed of termination 1, termination 2 and the cable as shown in Figure 2. The epoxy pipe, cryostat and current lead constitute termination 1. Current lead connects the HTS conductor to the electric source, its upper end is in atmosphere and lower end is immerged in LN2. The current lead will breed some heat during operation of the system and should be designed carefully. In our system, the current lead was made of Cu braid and has a length of 0.8m and a cross section of 400mm^2. At the joint between current lead and the cable, silver was plated to lower the contact resistance, and the joint was also designed skillfully so that the termination and the cable can be easily assembled at the installation field. The cryostat of termination isolates the heat from the system, and was made of SUS304 stainless steel. It was in high electric potential during operating, so a pipe made of fiber-epoxy and silicon aerogel is used to isolate the heat from system and also isolate the high electric potential of termination from the zero electric potential of the cooling system. On top of the termination, a heat exchanger was installed which helps release the heat from the upper of the current lead [3-4]. The cable is a HTS cable with warm dielectric and has a counter-flow cooling structure, which means LN2 getting into the cable through the former and returning from the annular room between the inner wall of cryostat and the outer wall of the HTS tapes[5]. Termination 2 is almost the same as termination 1, but without the epoxy pipe. In the 4m HTS cable system, high voltage toroid or ground potential toroid and outdoor porcelain are also included to satisfy the demands of electric parameters.

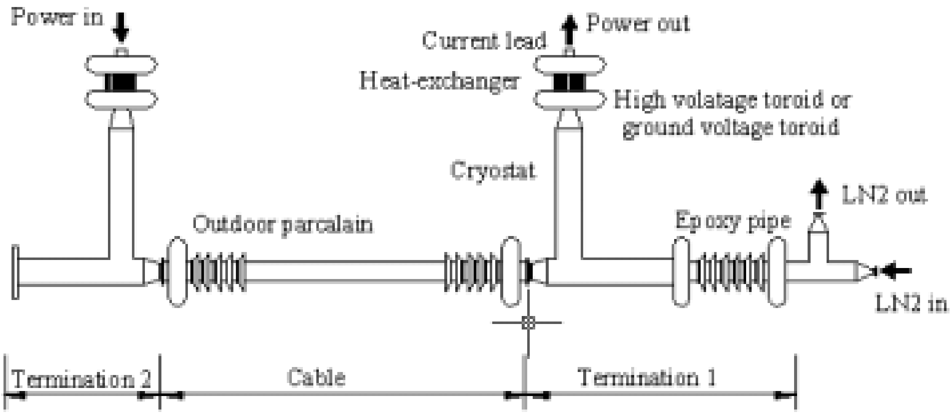


Figure 2 Schematic diagram of HTS cable and terminations

EXPERIMENT OF THE 4m HTS CABLE

In order to investigate the properties of a HTS cable system, some experiments are designed and executed before and after building the 4m HTS cable system. In this section, we give some test data on the heat loss.

Table 2 Test results of the components.

Current(A)	0	500	1000	1500	2000
Heat from conductivity of current leads（W/unit）	41.03	43.56	44.4	45.26	47.26
Heat from joule loss of current lead（W/unit）	0	4.87	19.56	44.17	79.12
Heat-leak of cryostat of termination 1(W/unit)	8.7				
Heat-leak of cryostat of termination 2(W/unit)	9.9				
Heat-leak of epoxy pipe(W/unit)	34.6				
Heat-leak of cryostat of the cable(W/m)	1				
Ac loss of the cable（W/m）	0	0.13	0.62	1.33	2.3
Total heat loss of the cable (W)	139.26	154.59	187.61	241.27	319.12
Heat loss of termination 2 (W)	49.73	57.1	72.62	98.1	135

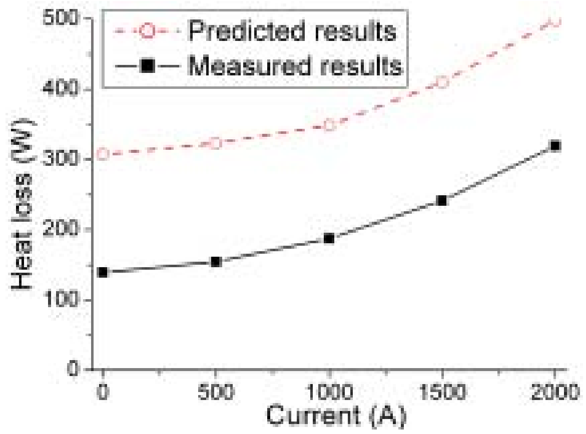
Test results of the components of the 4m HTS cable system are listed in Table 2. The tests were done before the assembling of the system. At the last two rows of Table 2, we roughly predicted the total heat loss of the HTS cable and termination 2. Among these results, the heat-leak of the cryostats and the epoxy pipe were tested by calorie method which means by the rate of evaporation of LN_2 [3-4]. The ac loss of the cable was obtained by testing the current, voltage and the phase angle between them [6]. The heat from conductivity and joule loss of the current leads are gained through the verified mathematical models and some test results [3-4].

After building the 4m HTS cable system, we did some test to get the total heat loss of the HTS cable and termination 2. The results are shown in Table 3.

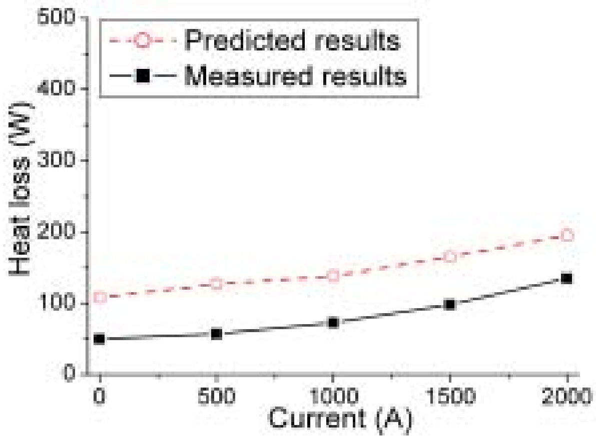
Table 3 Test results of the 4m HTS cable system

Current(A)	0	500	1000	1500	2000
Heat loss of the HTS cable (W)	307	323	348	410	498
Heat loss of termination 2(W)	108	127	138	165	195

Comparison between the predicted results and the measured results is shown in Figure 4. Measured results have the same rising trend as the predicted results with the increasing current, but are higher in value. For termination 2, the measured results are about 60~70W higher than the predicted results at different operating current. For the cable, the measured results are about 160~180W higher than the predicted results at different operating current. The difference of heat-loss between measured and predicted results for HTS cable and termination 2 vary little from one current value to another, so they are nearly irrelative to the current value. What caused this almost constant discrepancy? We quickly identified the problem that there was a bad thermal insulation on the terminations and the LN2 transmission line. The evidence for this conclusion was that the surface of termination 2 and the LN_2 transmission pipe at inlet and outlet of HTS cable are covered with frost during operation. This was the result of bad workmanship in assembling the termination and the LN_2 transmission pipeline. Taking out the discrepancy, we can see that the results by modeling and calculation are in good agreement with the experimental data, which indicates the designs of the cable conductor and the current leads meet our specifications. Now, the work to improve the thermal insulation of the terminations and the LN_2 transmission lines was done.



(a)



(b)

Figure 3 Comparison between the predicted heat-loss and the measured heat-loss at different current, and the y-axis represents the heat-loss of HTS cable in (a) and the heat-loss of termination 2 in (b)

SUMMARY

By building and testing a prototype 4m HTS power cable system, we have learnt the techniques of fabricating a HTS cable system. On the other side, we should pay a great attention to the workmanship in the manufacturing, transportation and installation processes. Till now, 30m,35kV/2kA HTS cable system have been installed and some tests are also finished, the results will be released in the near future.

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