Development and testing of 10.5kV/1.5kA HTS power cable

Lin Y. B., Gao Z.Y., Ning Z., Dai S. T., Teng Y. P.*, Xu L., Lin L. Z., Xiao L. Y.

Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100080, China
*Gansu Changtong Cable Science & Technology Co., Ltd., Gansu, China

A 10-m long, 3-phase, 10.5 kV/1.5 kA HTS power cable system has been built and tested. The warm dielectric cable includes 3 single-phase HTS cables using different winding schemes. The critical current of the cable is more than 2800 A and the total joint resistance of the conductor is less than 0.12 μΩ at 74 K. The AC loss measurements showed the loss is less than 0.85 W/m at 74 K and 1.5 kA_{rms} / 50 Hz. The cable has been operated stably and reliably at rated current for more than 5 hours continuously many times.

INTRODUCTION

Along with the rapid growth of the national economy in China, the electric utility is facing an ever-growing demand for electricity and the necessity of large capacity power transmission. HTS power cables, with 3 to 5 times more transmitted power than conventional cable of the same size, can meet increasing power demand in urban areas without renewing the existing cable ducts. The power transmission loss in China accounts for 8.5 % of the total electricity output each year, and is roughly equivalent to the future annual output of the Three Gorges Hydropower Station. Using HTS power cables, the power loss in the transmission line can be reduced at a percentage of 50 %, and this will save a large amount of electricity.

Under the support of the High Technology & Development Program of China and Gansu Changtong Cable Science & Technology Company Limited, R&D project of a 75-m long, 3-phase, 10.5 kV/1.5 kA HTS power cable system was initiated in April, 2002. Taking the lead, the Institute of Electrical Engineering, Chinese Academy of Sciences is developing the cable system in close collaborations with the Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, and Gansu Changtong Cable Science & Technology Co., Ltd. As an important stage of the project, a 10-m long, 3-phase, 10.5 kV/1.5 kA HTS power cable system was developed and tested successfully in August, 2003. This paper presents the development and testing results of the 10-m long HTS power cable.

DESIGN OF HTS CABLE

Structure of the cable

The cable is warm dielectric. Compared with cold dielectric cable, about half amount of HTS tapes can be saved, and the conventional dielectric technique can be adopted, thus the cost of HTS cable is reduced. Another advantage of the HTS cable with the warm dielectric is that its impedance matches that of a conventional cable of similar diameter, so it can easily replace a conventional cable in cable retrofit.

10-m long, 10.5 kV/1.5 kA HTS power cable includes 3 single-phase HTS cables with the warm dielectric. Figure1 shows sketch of each single-phase HTS cable. The conductor consists of 4 layers of HTS tapes spirally wound on a flexible stainless steel former. Thin Kapton tape was used for insulation between conductor layers to reduce ac losses due to the electromagnetic coupling of each layer. The cable core was housed in a cryogenic envelope. Sub-cooled liquid nitrogen flowed through the inside of former and the space between the cable core and the inner pipe of cryogenic envelope. The warm dielectric construction, a copper shield and a PVC cover were applied over the cryogenic envelope.

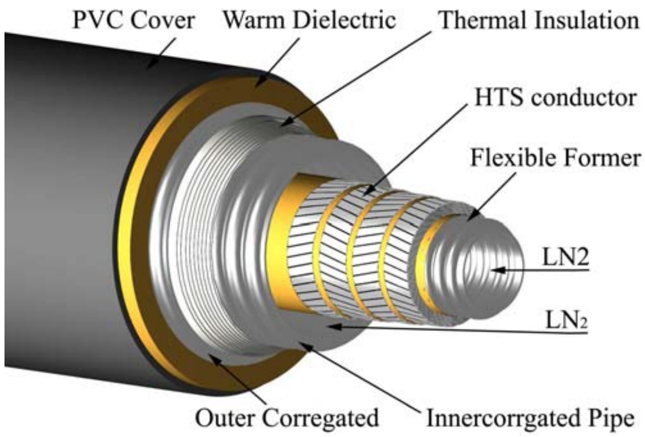

Figure 1 Sketch of a single-phase HTS cable

Table 1 Specifications of the VAC tapes

Parameter		Value
Width and thickness	(mm)	4.0 × 0.23
Number of filaments		121
Twist of filaments	(mm)	8
Length of single tapes	(m)	100 to 200
Dc critical current at 77 K	(A)	65 to 75
Critical tensile stress	(MPa)	100
Critical tensile strain	(%)	0.21
Minimum bend diameter	(mm)	70

Design of cable conductors

HTS tapes for our cable were multifilamentary Bi-2223/Ag/AgMg tapes supplied from Vacuum schmeltze, Germany. Specifications of the tapes are listed in Table 1. Three single-phase cable conductors rated current of 1.5 kA $_{rms}$ needed 4 layers of the HTS tapes for each one.

Based on our previous works [1, 2], the optimum design method of the cable conductor has been developed. The essentials of optimum design can be generalized as follows:

▪ Both I_c and n values should be used as criterion of the selected HTS tapes to ensure cable nice performance.

▪ The magnetic field acting on cable tapes should be minimized to reduce I_c degradation and AC losses.

▪ The current distribution among conductor layers should be as uniform as to gain most efficient use of HTS tapes and to reduce AC losses.

▪ The strains experienced by HTS tapes due to thermal contraction and bending must be limited in order to minimize the I_c degradation of HTS cable.

▪ The HTS tapes or insulation tapes in cable conductor should be wound at adequate butt gaps to avoid the damage to HTS tapes and crinkling of the insulation due to cool-down and bending of the cable.

Design of conductors with very low AC losses

Various methods to reduce AC losses of cable were developed and used in three single-phase cable conductors. A special method with the equal winding pitch was used in phase-A conductor. In this method, the critical currents in outer conductor layers are higher than that in inner layers to gain most efficient use of the tapes, and the winding direction of adjacent layers is opposite to eliminate the axial magnetic field. Schemes with uniform current distribution were used in other phases. After the radius of conductor layers are given, the uniform current distribution can be realized by adjusting the winding pitches and directions of conductor layers. For phase-B, all conductor layers were wound in the same direction. For phase-C, two inner layers and two outer layers were wound

Table 2 The design parameters of cable conductors

Parameter	Phase-A	Phase-B	Phase-C
first layer pitch(mm)	306	305	190
2nd layer pitch(mm)	306	282	463
3rd layer pitch(mm)	306	239	445
4th layer pitch(mm)	306	193	134
Number of tapes	74	72	70

in the opposite direction. The design parameters of cable conductors are shown in Table 2.

FABLICATION OF HTS CABLE

The cable conductors were wound according to the designed parameters. The HTS tapes were soldered to the copper terminals using the low-melting-point alloy solder. The skid wires were wound on the conductors for protection. The cryogenic envelopes comprised double stainless steel corrugated tubes that provide high vacuum and super-insulation without maintenance. The cross-linked polyethylene insulation triple-extruded, the copper shield and PVC cover were applied over the cryogenic envelope. There were the semiconductors on each side of the dielectric to smooth electrical field.

The general view of the HTS cable with its terminations is shown in Figure 2. The main parameters of the HTS cable are given in Table 3.

Figure 2 The general view of the HTS cable system

Table 3 The main parameters of the HTS cable

Parameter		Value
Outer diameter of former	(mm)	25.7
Inner/Outer of conductor	(mm)	25.8/28.1
Outer diameter of skid wires	(mm)	33.0
Inner/Outer of Cryogenic envelope	(mm)	39/83
Thickness of warm dielectric	(mm)	5.0
Thickness of copper shield	(mm)	0.4
Thickness of PVC cover	(mm)	6.0
Outer diameter of HTS cable	(mm)	113.8

TESTING OF HTS CABLE

Integrated with a cryogenic system, two terminations, the power supplies and monitoring system, the 3-phase cable was tested. The cryogenic system for cable cooling can supply circulating subcooled LN_2 at temperatures of 67-77K and pressures up to 4 bars. LN_2 from cryogenic system went into phase-B and phase-C in parallel, returned in phase-A. The monitoring system includes a real-time monitoring system for temperature and pressure, *V-I* measurement system and AC operation monitoring system for cable.

Dc *V-I* characteristic and joint resistances

E-I characteristics of 3 single-phase HTS cables were measured. All their electric fields are equal to zero at the currents up to 2710A, which is the limit of our dc power supply. *E-I* curve of phase-C cable is shown typically in Figure 3.

The I_c of more than 2800 A at 1μV/cm criterion can be estimated. Total joint resistances of cable conductors were measured also. The resistances of phase-A, phase-B and phase-C are 0.119μΩ, 0.066 μΩ and 0.072μΩ respectively.

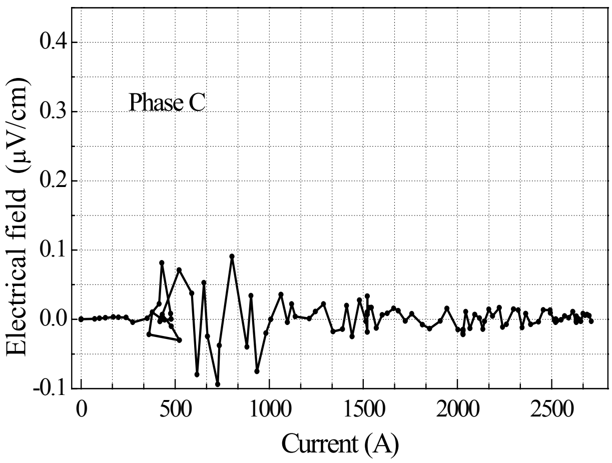

Figure 3 *E-I* curve of phase-C cable at 74K

AC losses of conductors

AC losses of conductors were measured electrically. The AC loss curves are shown in Figure 4 and compared with theoretical curve based on monoblock model [3] at 74 K and 50 Hz. At 1.5 kA $_{rms}$ the ac losses of the phase-A, phase-B and phase-C conductors are respectively 0.42W/m, 0.5W/m and 0.85W/m, which are less than the theoretical value.

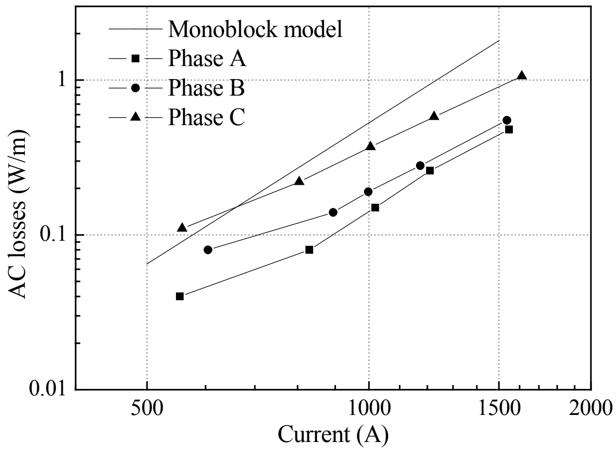

Figure 4 AC loss curves of cable conductors

Long-time operation and thermal cycle tests

The cable has been operated stably and reliably at rated current for more than 5 hours continuously 5 times. Typical Long-time test curves of cable are shown in Figure 5. The cable has experienced 6 thermal cycle tests up to present and not any I_c degradation of the cable is observed.

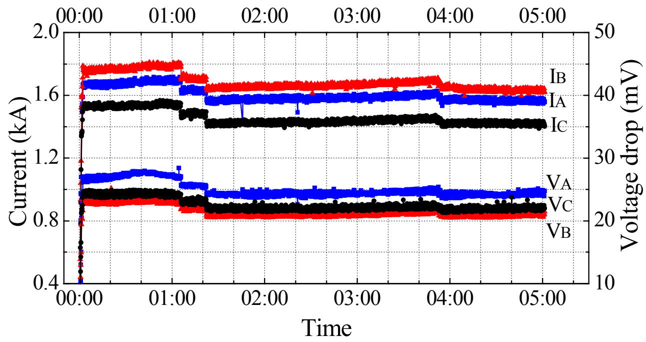

Figure 5 Long-time test curves of cable

AC withstand tests of dielectric

The dielectrics of HTS cable were subjected to the ac withstand tests to 35 kV for 4 hours without any breakdown before and after bending of 1.8 m in bending diameter.

CONCLUSIONS

Critical current of the HTS cable is more than 2800 A which exceeds the designed target. Long-time operation and thermal cycle tests indicated that the performance of the cable is stable.

The joint resistances and ac losses of cable conductors are very low. This proved that joint weld technique and the methods to reduce AC losses of cable are very useful.

The tests of HTS cable indicated that the design and development are successful. The reliable data and practice got from the development and tests of the cable can be used for development and operation of the 75m, 10.5kV/1,5kA HTS power cable.

ACKNOWLEDGEMENT

The authors appreciate Dr. D. Hui, Dr. F.Y. Zhang, Mr. H.D. Li and Q. Bao for their support and assistance during the testing of the cable.

REFERENCES

1. Lin, Y.B., Lin, L.Z., Li, S.P., Zhang, F.Y., Chen, S.F., Wang, Y.S., Xu, L., Song, N.H., Wen, H.M., and Li, J., Development of A 1000A Class Bismuth-Based HTS Model Cable, Advances in Cryogenic Engineering (2000) 45 1589-1595

2. Lin, Y.B., Lin, L.Z., Gao, Z.Y., Wen, H.M., Xu, L., Shu, L., Li, J., Xiao, L.Y., Zhou, L., and Yuan, G.S., Development of HTS Transmission Power Cable, IEEE Trans. on Applied Superconductivity (2001) 11 2371-2374

3. Vellego, G. and Metra, P., An analysis of the transport losses on HTSC single-phase conductor prototypes, Supercond. Sci. Technol. (1995) 8 476-483