Design and Characteristic Study of a Novel Internal Cooling High Temperature Superconducting Composite Cable with REBCO for Energy Storage Applications

Jiahui Zhu, Panpan Chen, Hongjie Zhang, Ming Qiu, Huiming Zhang, Jun Gong, Yuanyuan He and Min Zhang

***Abstract*—High temperature superconducting magnetic energy storage systems (HTS SMES) have attracted significant attention for fast response and ensure a reliable power supply. However, the current carrying capacity of single superconducting tape often meets limitation for the large scale HTS SMES applied in the power grid. Therefore, a high temperature superconducting composite cable with inner helical cooling tunnel and kA class current carrying ability is proposed for SMES magnet by using REBCO tape. The critical current characteristics of this internal cooling composite cable are analyzed considering the influence of anisotropy in magnetic field. A 100 m length, high temperature composite cable is manufactured in China Electric Power Research Institute (CEPRI). The critical current experimental system with a 3 kA DC current power source and a high-precision Digital Data Acquisition (DAQ) system have been set up to investigate the current carrying ability of a straight and a bending demo composite cable in LN2. The results show that critical current of HTS composite cable consisted of 4 REBCO tapes can achieve 780 A at 77 K self-field and the experimental I-V curve of each REBCO tape in the composite cable is not uniform because of the influence of anisotropy. When the HTS composite cable is bent, its critical current is about 90% of the straight HTS composite cable. Therefore, the design method and the proposed experimental system are proved to be effective as well.**

***Index Terms*—High temperature superconducting composite cable, inner helical cooling, REBCO, SMES**

I. Introduction

High temperature superconducting energy storage system (HT SMES) stores energy in the magnetic field produced by a persistent current in a superconducting loop. So that HT SMES has several significant advantages: a) larger power density than other energy storage system, b) more than 85% efficiency, c) a substantially faster response speed, d) infinite charge and discharge cycles [1].

There are several completed and ongoing HTS SMES projects for power system applications [2, 3]. Superpower Inc, Houston University and Brookhaven National Lab are aiming to deliver a 2.5 MJ system for load leveling in medium voltage 15-36 kV distribution networks. In 2013, Germany also proposed a new type of 48 GJ hybrid energy storage system LIQHYSMES to solve the problem of grid fluctuation caused by renewable energy integration [4]. Form these above application, we find the large capacity energy storage magnet usually wants the current can be as large as possible. However, the critical current of single commercial HTS tape used in SMES can't meet this requirement. And it is difficult and costly to increase the current by paralleling coils or lowering the operating temperature.

In recent years, there are some literatures describing different kinds of superconducting composite conductor, such as twisted stacked-tape cable (TSTC) [5-8]. However, they didn't have enough considerations for the power grid application, for example in SMES. In 2016, China Electric Power Research Institute (CEPRI) has firstly designed a 3 MJ HTS SMES applying a proposed twisted stacked-tape in tube (TSTT) composite cable [9].

This paper proposes a TSTT composite cable integrated by four REBCO tapes and a constant aluminum jacket. The electromagnetic characteristics and current variation considering the anisotropy of REBCO and critical current are analyzed by using COMSOL software. A 100 m length, TSTT composite cable is manufactured and tested in CEPRI for the first time. The calculated and measured critical current of a straight and a bent TSTT composite cable are compared. The results show that the critical current of TSTT composite cable has achieved 780 A@77K which satisfied the current performance requirement for winding a 3 MJ HT SMES.

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II. Internal Cooling High Temperature Composite Cable Design

A. Structure design

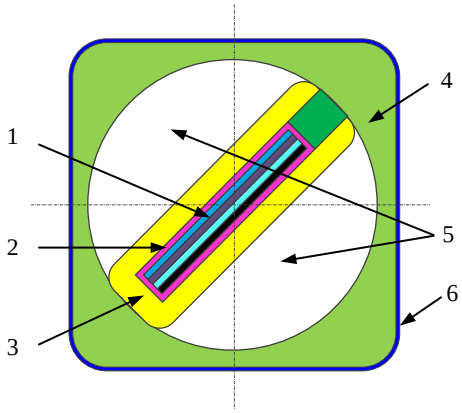

Fig. 1. sketch of inner helical cooling TSTT composite cable.

The structure schematic diagram of the composite cable is shown in Fig.1. It mainly consists of six parts: (1) superconducting core. It has 4–ply REBCO superconducting tapes stacked in parallel and twisted in a certain pitch (the total number of tapes can be increased); (2) soft metal buffer layer using silver-plated copper wire; (3) inner aluminum coating layer; (4) aluminum jacket with square outer wall and round inner wall; (5) cooling channel flowing liquid nitrogen or gas helium; (6) insulation layer of polyimide film.

This composite cable has some advantages for constructing a SMES. Firstly, the stacked tapes have been twisted so the anisotropy of HTS wires can be reduced to make current distribution more uniform, which is beneficial to enhance the critical current and reduce AC losses. Secondly, the spiral inner cooling channels can increase the contact surface to improve the cooling efficiency of magnet. Thirdly, the aluminum jacket acts as a stabilizer to withstand the fault current for SMES quench protection. Finally, the compact structure can greatly reduce the size of the high temperature energy storage magnet. The specification of a TSTT composite cable has shown in Table.1.

TABLE I
SPECIFICATION OF THE INTERNAL COOLING TWISTED STACKED-TAPE IN TUBE COMPOSITE CABLE FOR HTS SMES

Parameters	Value
Sectional dimension	13mm×13mm
Length	100m
Inner diameter	10.8mm
Pitch	>200mm
Superconducting core size	9.6mm×4.8mm
Thickness of soft metal buffer layer	0.5mm
Critical tensile stress (77 K)	250 MPa
Critical tensile strain (77 K)	0.3%
Minimum bending diameter	300mm
REBCO tape number	4
Critical current (77K)	700 A
Length per cable	100m

B. Critical current characteristics analysis

A T-A equation model is applied for the first time to calculate the magnetic field and current distribution of each REBCO tape in the composite cable considering the influence of anisotropy in magnetic field. It is a general, flexible and efficient FEM model which can be implemented in commercial FEM software to analyze complex geometries. The T-A governing equation based on Faraday's law is shown in (1):

$$\nabla \times E \cdot \mathbf{n} + \frac{\partial B}{\partial t} \cdot \mathbf{n} = 0 \tag{1}$$

Since the T-A model approximates the superconducting layer as a sheet, the Faraday's law is applied to the sheet geometry. The difference is that a normal vector **n** is applied in (1). Then, *E-J* power law is employed as

$$E = E_0 \left(\frac{|J|}{J_c} \right)^n \frac{J}{J_c} \tag{2}$$

And J is calculated as

$$J = \nabla \times T \tag{3}$$

Where, T is current vector potential, n is the n-value of superconducting tape. The magnetic flux density B is solved using the traditional **A** formulation, seen in (4). $Jc(B)$ is calculated by (5):

$$\nabla \times \nabla \times A = \mu_0 J \tag{4}$$

$$J_c(B) = J_{c0} \left(1 + \frac{1}{B_0} \sqrt{\gamma^{-2} B_{\parallel} + B_{\perp}} \right)^{-\alpha} \tag{5}$$

$B_{/\!/}$, $B_{\perp}$ are the parallel and perpendicular magnetic filed components; I_{c0} is the critical current of superconducting tape at 77K, self-field; B_0=20 mT; γ=5, α=0.65 [10]。

The FEM mesh for a 10 cm length, 3D TSTT composite cable is built by using COMSOL software, seen in Fig.2. The electromagnetic solve equation is replaced by the T-A equation model with applying current to the superconducting tapes by setting the edges. The magnetic flux density and critical current of the demo composite conductor is calculated based on J_c-B relationship. The theoretical critical current is 913 A@77 K.

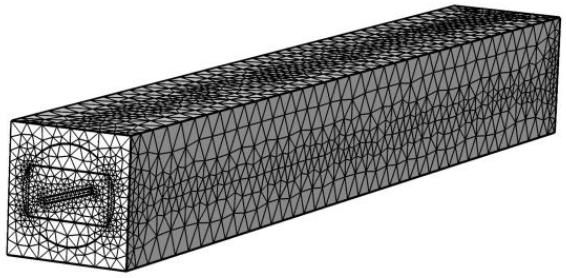

Fig. 2. The mesh of TSTT composite cable based on 3D FEM in COMSOL.

III. Manufacture and Critical Current Experimental Tests of the Composite Cable

A. Continuous HTS Composite Cable Manufacturing

In this paper, China Electric Power Research Institute (CEPRI) design the manufacturing process of high temperature superconducting internal cooling twisted stacked-tape in tube (TSTT) composite cable using Fujikura REBCO tapes. A continuous TSTT composite cable with 100 meters is manufactured in Anhui Hong Yuan Special Cable Group co. LTD in China. The industrial manufacturing process photo of insulation coating process for the 100 m composite cable is shown in Fig. 3. Then, a 1.5 m demo cable is cut off from the 100 m cable and to be tested for its critical current characteristic after the industrial manufacturing.

Fig. 3. Photo of 100 m HTS composite cable in insulation coating process.

B. The critical current testing system for TSTT cable

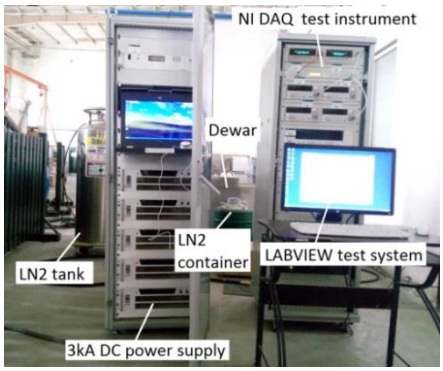

Fig. 4. *V-I* test system photo for composite HTS cable.

The *V-I* test platform photo is shown in Fig. 4. The test system consists of a NI Data Acquisition (DAQ) test instrument, a 3 kA DC power supply with quench protection circuit and a cryogenic dewar. A 1.5 m demo composite cable is placed in a vessel which is filled with liquid nitrogen at 77 K. Each superconducting tape is connected to the 3 kA DC power supply through a silver current lead in the *V-I* test system. The cross section of a silver current lead is 10 mm×0.4 mm. There are several voltage leads both on REBCO tapes and silver current leads. And they are all connected to the DAQ test instrument. All of the current and voltage signals of TSTT composite cable are collected by DAQ system. Therefore, the current sharing characteristics in the composite cable can be obtained according to the voltage signals of the silver leads and their resistance. So, the experimental *V-I* curve and the quench state of the 1.5m demo TSTT composite cable is obtained. In the experiment, the shunt ratio for the total current is 2000 A/75 mV, the charging rate for the composite cable is 2 A/s and the discharging rate is 5 A/s. Fig.5 is the 1.5 m TSTT composite cable with 160 mm bending radius.

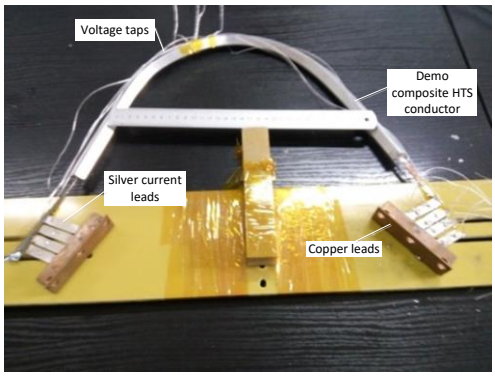

Fig. 5. Photo of silver current lead and welding condition of voltage leads for 1.5m TSTT composite cable with 160mm bending radius.

C. Critical current testing for straight composite cable

Fig. 6 is the *V- I* curves of four REBCO tapes which are in a straight TSTT composite cable. The critical currents of four HTS tapes are 211 A，215 A，236 A and 237 A, respectively. The critical current of the 1st tape and 2nd tape are both less than that of the 3th tape and 4th tape. This decrease in the critical current may be due to the damage caused by the composite cables in the manufacturing process, or in the welding process due to the high temperature environment. Compared to the critical current of single REBCO tape with 270 A@77 K, the critical currents of four tapes have decreased by 21.85%, 20.37%, 12.59% and 12.22%. The maximum reduction ratio of 1st tape is nearly 22%.

Fig. 7 is the critical current curve for the TSTT composite cable. When one tape takes place quench at the first time, we add the current of each tape at this moment as the overall critical current of the cable. According to the transition criterion (1 μV/cm), the critical current is 780 A and it is 85.43% of the theoretical value of 913 A.

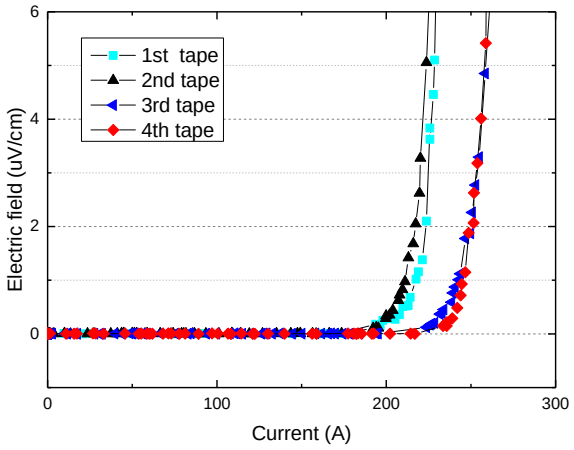

Fig. 6. Experimental *V-I* curve of each REBCO tape in HTS TSTT composite cable.

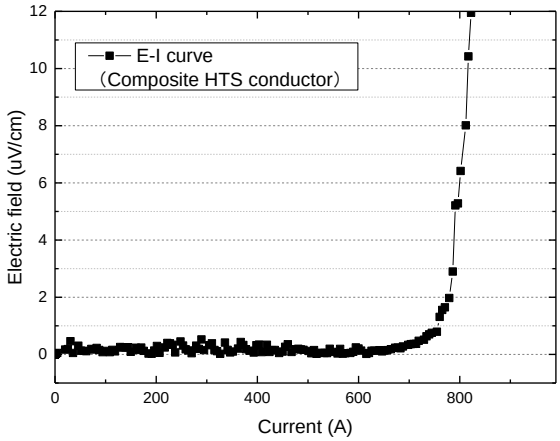

Fig. 7. Experimental *V-I* characteristic of HTS TSTT composite cable.

D. Critical current testing for composite cable with bending

To investigate the bending effect on the critical current in the process of winding, this article has carried on a critical current test of composite cable with the bending radius of 160 mm which is the inner radius of a pancake for a superconducting energy storage magnet [11].

Fig. 8 is the *V- I* curves of four REBCO tape in a bending composite cable. Fig. 9 is the *V- I* curve for the composite cable after bending. In Fig. 8, the critical currents of four HTS tapes are 183 A，185 A，218 A and 220 A@77 K. These critical currents have decreased by 32.22%, 31.48%, 19.25% and 18.51% compared to the critical current of a REBCO tape, respectively. The critical currents of the 1st tape and 2nd tape that have been damaged in the process of manufacturing are more attenuated than that of the 3th tape and 4th tape. The critical current of the bending composite cable is 700 A which is 89.74% of that of the straight composite cable. It is shown that bending leads to further reduction of the critical current for composite cable.

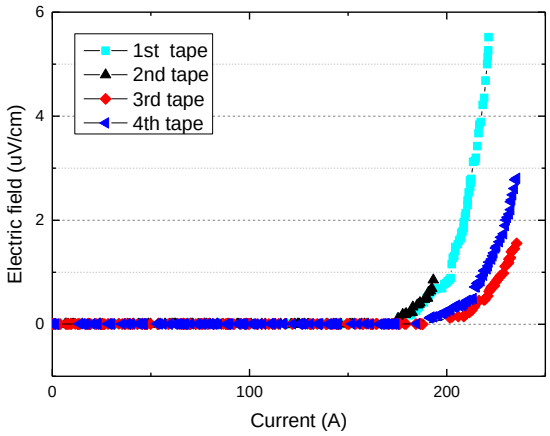

Fig. 8. Experimental *V-I* curve of each REBCO tape in HTS TSTT composite cable with 160 mm bending radius.

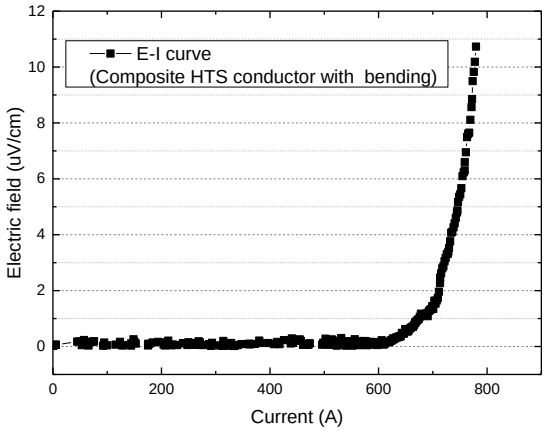

Fig. 9. Experimental *V-I* characteristic of HTS TSTT composite cable with 160 mm bending radius.

E. Comparison and analysis

Considering the influence of magnetic field and mechanical processing, the calculated critical current of the composite cable is 913 A. After manufacturing, the critical current reduces to 780 A and further to 700 A with a bending radius of 160 mm. Compared to the theoretical value, the critical current reduction ratio of straight and bending HTS TSTT composite cable are 14.5% and 23.3%, respectively, as in Table.2. When the composite cable is bent, its critical current is nearly 90% of the straight one. Therefore, the composite cable meets the critical current performance requirements. It is feasible to use this composite cable to make a designed MJ class SMES magnet. We will give these research achievements in future.

TABLE II
THE CRITICAL CURRENT COMPARISON BETWEEN CALCULATION AND EXPERIMENTAL RESULTS OF TSTT COMPOSITE CABLE

Item	Theoretical value	Experimental Ic value of composite HTS conductor	
		Straight	Bending
Critical current /A@77K	913	780	700
Reduction ratio	-	14.5%	23.3%

IV. CONCLUSION

A high temperature superconducting twisted stacked-tape in tube (TSTT) composite cable is proposed in CEPRI with a spiral cooling tunnel inside and a metal jacket. A T-A equation model is applied to calculate the theoretical critical current of the TSTT composite cable. A continuous TSTT cable with 100 meters is manufactured in China. The critical current experimental system is built for the composite cable. Compared to the theoretical value with 913 A@77 K, the critical current reduction ratio of straight and bending TSTT composite cable are 14.5% and 23.3%. In addition, after the composite cable is bent, its critical current is nearly 90% of the straight one. Therefore, the composite cable is considered as the potential superconducting material for a MJ SMES magnet.

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